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MODELLING OF HEAVILY LOADED LUBRICATED CONTACTS

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This technical report has been reviewed and is approved for publication.

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Thermal elastohydrodynamic (EHD) lubrication of rolling/sliding line contacts is investigated to develop an interactive computer program for prediction of lubrication system performance. The user inputs lubricant and mechanical system physical properties as well as operating conditions of load and speed for calculation of contact zone pressure, temperature, traction, and stresses. This program is one of the first to include thermal effects in calculations and, therefore, can more accurately assess the critical tribological performance parameters at high load and speed conditions than previous prediction models. The program is written in the FORTRAN language and utilizes a UNIX operating system for high quality graphic output allowing easy visualization of results.

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PREFACE

The technical report was prepared by the Tribology Laboratory, School of Mechanical Engineering, Purdue University, Purdue Research Foundation, West Lafayette, Indiana and the Lubrication Branch, Fuels and Lubrication Division, Aero Propulsion and Power Directorate (APPD), Wright Laboratory (WL), AirForce Systems Command (AFSC), Wright Patterson Air Force Base, Ohio. The work was accomplished and administered under task 8 of the Battelle Corporation Scholarly Research Program Project 3048, Task 304806, Work Unit 30480639, during the period March 1990 to August 1991. The effort was funded by the In-House Laboratory Independent Research (ILIR) Program and Project 3048, Task 304806, Work Unit 30480626, "Turbine Engine Lubricant In-House Research," with Mr. Robert L. Wright as Project Engineer.

LIST OF SYMBOLS

b	Half Hertzian width, m
c_f	Specific heat of the lubricant, J/kg-^oK
c_s	Specific heat of the solids, J/kg-^oK
D_{ij}	Influence coefficient of elastic deformation
E	Young's Modulus, Pa
E'	Equivalent Young's modulus, Pa
G	Material parameter
h	Film thickness, m
$\bar{h}$	Normalized constant, m
H	Dimensionless film thickness
H_e	Dimensionless film thickness at exit point
H_o	Dimensionless film thickness constant
k_f	Thermal conductivity of the lubricant, W/m-^oK
k_s	Thermal conductivity of the solids, W/m-^oK
$\tilde{k}$	defined as, $k_f/(r_o\bar{u}b)$, J/kg-^oK
K	Dimensionless constant, $(p^2U)/16W^2$
p	Pressure, Pa
p_H	Maximum Hertzian pressure, Pa
P	Dimensionless pressure
R	Equivalent radius of contact, $1/R = 1/R_1 + 1/R_2$, m
t	Temperature, ^oK
T	Dimensionless temperature
T_1	Dimensionless temperature on bottom surface
T_2	Dimensionless temperature on top surface
T_o	Inlet temperature
u	Velocity in the x direction, m/sec
$\bar{u}$	Average rolling velocity, m/sec
U	Dimensionless velocity in X direction
U_1	Dimensionless velocity of the bottom surface
U_2	Dimensionless velocity of the bottom surface
U^*	Dimensionless speed parameter
U_{av}	Dimensionless average velocity on local element
U_d	Dimensionless slipping ratio (also S)
v	Velocity in y direction, m/sec
V	Dimensionless velocity in Y direction
w	Applied load per unit length, N/m
W	Dimensionless load parameter
x	Coordinate along the rolling direction, m
X	Dimensionless coordinate in the rolling direction
X_{end}	Exit position
X_{min}	Inlet position
Y	Dimensionless depth into the lubricant film
z	Exponent for Roelands' viscosity model
a	Pressure-viscosity coefficient, m^2/N
b	Coefficient of lubricant thermal expansion, $^oK^{-1}$
g	Temperature-viscosity coefficient, $^oK^{-1}$
q_o	Ambient viscosity of the lubricant, N-sec/m^2
$\bar{\eta}$	Dimensionless viscosity of the lubricant

$\bar{\mu}_o$	Ambient viscosity of the lubricant, N-sec/m^2
$\bar{\mu}$	Dimensionless viscosity of the lubricant
r_o	Ambient density of the lubricant, kg/m^3
r_s	Density of the solids, kg/m^3
$\bar{\rho}$	Dimensionless density of the lubricant
n	Poisson's ratio
L	Dimensionless normalized constant, $\bar{h}$/b

INTRODUCTION

The prediction of lubrication performance parameters in the bearing or gear contact zone is an important tool in forecasting the type of lubricants or lubrication system materials needed in particular tribological applications. The Air Force's effort to develop highly thermodynamically efficient advanced turbine engines will required that liquid lubricants and lubrication system materials, such as bearings and gears, be found that can operate successfully under conditions of extremely high loads, speeds and temperatures. Setting aside the thermal and oxidative stability problems faced by the lubricant in these situations, one must be sure that the lubrication properties of the fluid will be satisfactory enough under these strenuous conditions to allow adequate separation of the moving surfaces in the bearing or gear system. Also, the pattern and level of stresses placed on the bearing or gear materials must be assessed to determine if the materials will be able to endure the set conditions.

Currently, the only way to adequately assess lubricant and lubrication system performance in extreme tribological conditions is to run time consuming and expensive rig tests. If the lubricant/lubrication system combination fails, much time, effort and money has been wasted, although valuable lessons may have been learned. It would be very helpful to have in place a method of theoretical prediction of lubricant/lubrication system material performance to allow only the most promising lubricant and material combinations to be selected for advanced turbine engine bearing or gear rig testing. Unfortunately, most theoretical prediction models fall short of the ability to act as adequate screening tests for extreme tribological conditions due to their failure to include contact zone thermal effects into calculation regimes. Many of these models work very well for predicting performance at low load and speed conditions because the pressure effects in the contact zone are well characterized and the contribution to performance parameters by thermal effects is not very significant. At high load and speed conditions, however, the extreme stresses put on the lubricant and bearings or gears has been observed to create large temperature rises in the contact zone, thereby negatively impacting lubricant viscosity, surface separation, traction and stress levels of the lubrication system materials. If thermal effects are not considered in these instances, the theoretical model will give results that are highly inaccurate. They will mislead one into believing that viscosity, surface separation, traction and material parameters are much better than they actually would be in a real system.

The goal, therefore, of the Air Force in sponsoring the work of Dr. Sadeghi's tribology group at the Purdue Research Foundation was to develop accurate theoretical modeling of extreme tribological systems in the form of an easy to use, interactive computer program. Dr. Sadeghi and his co-workers have pioneered the inclusion of thermal effects into a sophisticated tribological predictive model that helps the user understand the type of conditions that will exist within the contact zone and in the system materials as parameters such as load and speed are widely varied. The following pages describe the theoretical model and the computer program which allows the user to input the various physical properties of the lubricant and bearing or gear material as well as the load and speed conditions of interest and then calculate the lubricant film thickness, traction, contact zone pressures, temperatures, and material stress patterns and levels to allow determination of likely lubricant and lubrication system performance. The results are then shown in an easily visualized graphic mode. A more accurate prediction model, such as this, gives the Air Force a very useful tool to preliminarily screen various lubricant and lubrication system material combinations for their likely capability to meet particular mission profiles within advanced turbine engine environments. The computer program allows one to determine the most promising candidates for a particular range of conditions and conversely the limitation of conditions for given candidates. This has the capability to save greatly on time, effort and money in the selection process of lubricants and materials for advanced turbine engine tribological system development.

OBJECTIVE

The objectives of this study have been to investigate thermal elastohydrodynamic (EHD) lubrication of rolling/sliding line contacts. In order to achieve objectives, several computer models were developed for Newtonian and non-Newtonian fluid rheology models to determine pressure, temperature, traction, mechanical and thermal stresses at the lubricated contact interface of two machine elements. Using these models, an interactive computer graphics has been developed to aid in the analysis and design of EHD lubrication of rolling/sliding machine components.

This report provides a description of the method of solution, the computer models developed, the computer aided design graphics package, and a sample of the results.

THEORETICAL MODELLING OF TRIBO-CONTACTS

Rolling/sliding machine elements such as bearings, gears, cam and its followers, etc., are frequently subjected to high loads, speeds, and slip conditions. These elements support the load and allow the rolling/sliding motion inherent in the mechanism to take place. The study of heavily loaded lubricated rolling/sliding contacts in which the elements elastically deform (Elastohydrodynamic, EHD) has been investigated extensively in recent years. Most of the initial study of EHD lubrication focused on the isothermal and steady state conditions for a Newtonian lubricant, and the evaluation of the film thickness was the main concern. However, recently Sadeghi and Dow [1] illustrated that temperature has a significant effect on the lubrication process.

Sternlicht et al., [2] were among the first to introduce the temperature effects on EHD lubrication. Cheng [3] presented a solution to the problem of thermal EHD lubrication; however, the loads considered were extremely low, and his results indicated small change in the film thickness. Dowson and Whitaker [4] considered the temperature effects on EHD lubrication; however, their results indicate insignificant thermal effects. Murch and Wilson [5] illustrated that temperature has a significant effect on the film thickness particularly at high speeds. Kaludjercic et al., [6] presented a formula for the reduction in the minimum film thickness caused by viscous heating in the film. Ghosh and Hamrock [7] presented a solution for EHD lubrication with thermal effects included; however, their model did not converge for high speed and high slip conditions. Sadeghi and Dow [1] in 1986 presented a complete solution to the problem of thermal EHD lubrication for heavily loaded rolling/sliding contacts. They illustrate that significant temperature rise occurs in the fluid film. However, their analysis requires measured pressure and surface temperature as boundary conditions. Sadeghi et al., [8] also present a formula for the temperature rise in the mid-film. They illustrate that their model correlates well with their finite difference analysis. Wang and Zhang [9] presented a solution on the thermal non-Newtonian EHD lubrication. The Reynolds equation considered in their solution does not include the thermal effects, and the loads considered were extremely low.

In this current research work, the models developed by Sadeghi and Sui [10-14] which employed the Newton-Raphson technique to solve the Reynolds equation and the control volume finite element method to solve the energy equation were tested over a wide range of operating conditions. These models include the following:

Newtonian fluid model - isothermal and thermal conditions
Hyperbolic fluid model - non-Newtonian isothermal condition
Re-Eyring fluid model - non-Newtonian isothermal and thermal conditions
Re-Eyring fluid model - non-Newtonian thermal condition including effect of thermal expansion of the solids.

Fluid Models

The models presented by Sadeghi and Sui [10-14] were developed for different types of lubricants. These lubricant types include Newtonian, Hyperbolic (non-Newtonian), and Re-Eyring (non-Newtonian).

Newtonian Fluid Analysis

This analysis is based on the Newtonian fluid model. The governing equations used in this analysis are the Reynolds equation the elasticity equation and the energy equation with the fluid properties (viscosity and density) represented as functions of pressure and temperature. When the temperature effects within the lubricant are neglected (isothermal), the Newton-Raphson technique [10-14] is used to solve the simultaneous system of Reynolds and elasticity equations. When considering a variation of temperature within the lubricant (thermal), the Newton-Raphson technique [14] is employed to solve the simultaneous system of Reynolds and elasticity equations for pressure and then the control volume finite element method [15] is used to solve the energy equation for temperature. This process is repeated until the pressure and temperature have converged to a relative error of 1/1000 for each unknown.

Thermal Reynolds Equation

The integral form of the thermal Reynolds equation with the appropriate assumptions and boundary conditions in dimensionless form is given by [14]:

$$f_i = H_i^3\left(\frac{dP}{dX}\right)_i - K\frac{U_1}{(\overline{G}_2)_i}\left[H_i(\overline{G}_3)_i - H_e(\overline{G}_3)_e\right] - \frac{K\,U_d}{(\overline{G}_2)_i}\left[\frac{H_i(\overline{G}_1)_i}{(\overline{\mu}_e)_i} - \frac{H_e(\overline{G}_1)_e}{(\overline{\mu}_e)_e}\right] = 0 \tag{1}$$

with the boundary conditions:

$$P = 0 \qquad \text{for } X = X_{in}$$

$$P = \frac{dP}{dX} = 0 \qquad \text{for } X = X_{end} \tag{2}$$

and the constant load condition:

$$\int_{X_{in}}^{X_{end}} P\,dX = \frac{\pi}{2} \tag{3}$$

Energy Equation

The temperature field within the lubricant film is obtained from the solution of the energy equation. The energy equation in dimensionless form is [14]:

$$\Lambda^2\frac{\partial}{\partial X}\left(\tilde{\rho}UT - \tilde{k}\frac{\partial T}{\partial X}\right) + \frac{\partial}{\partial Y_1}\left(\Lambda\tilde{\rho}VT - \tilde{k}\frac{\partial T}{\partial Y_1}\right) = \tilde{\mu}\left(\frac{\partial U}{\partial Y}\right)^2 = \tilde{\beta}TU\left(\frac{dP}{dX}\right) \tag{4}$$

and the boundary conditions are:

$$T_a(X) = S_a \int_{X_{min}}^{X} \left(\frac{\partial T}{\partial Y_1}\right)_a \frac{dc}{(X-c)^{1/2}} \tag{5}$$

$$T_b(X) = S_b \int_{X_{min}}^{X} \left(\frac{\partial T}{\partial Y_1}\right)_b \frac{dc}{(X-c)^{1/2}} \tag{6}$$

Film Thickness Equation

The film thickness in the dimensionless form is given as [14]:

$$H_i = H_o + \frac{X_i^2}{2} + \sum_{j=1}^{N} D_{ij} P_j \tag{7}$$

Viscosity-Pressure-Temperature Equation

The Roelands viscosity/pressure relationship modified with the thermal effects is [14]:

$$\bar{\mu} = \exp\left\{\left[\ln\left(\mu_o\right) + 9.67\right]\left[-1 + \left(1 + 5.1 \times 10^{-9} P_H P\right)^z\right] + \gamma T_o (1-T)\right\} \tag{8}$$

Density-Pressure-Temperature Equation

The Dowson and Higginson density/pressure relationship modified with the thermal effects is [14]:

$$\bar{\rho} = \left[1 + \frac{0.6 \times 10^{-9} P_H P}{1 + 1.7 \times 10^{-9} P_H P}\right]\left[1 - \beta T_o (T - 1)\right] \tag{9}$$

The numerical procedure used for a complete solution of the governing equations is presented in.

Hyperbolic (non-Newtonian) Fluid Analysis

This analysis is based on the Hyperbolic fluid model. The governing equations are the Reynolds equation and the elasticity equation . The Reynolds equation is modified to include the non-Newtonian behavior of the lubricant [11]. The relationship between the shear stress and shear strain rate is assumed to follow the Hyperbolic fluid model. The Newton-Raphson technique is used to solve the simultaneous system of the modified Reynolds and elasticity equations for pressure while the temperature is assumed to remain constant throughout the lubricant indicating an isothermal condition.

Eyring (non-Newtonian) Fluid Analysis

This analysis is based on the Eyring fluid model. The governing equations are the Reynolds equation, the elasticity equation, and the energy equation with the fluid properties (viscosity and density) represented as functions of pressure and temperature. The Reynolds equation is modified to include the non-Newtonian behavior of the lubricant [10-14]. The relationship between the shear stress and shear strain rate is assumed to follow the Eyring fluid model. When the temperature effects within the lubricant are neglected (isothermal), the Newton-Raphson technique is used to solve the simultaneous system of the modified Reynolds and elasticity equations. When considering the variation of temperature within the lubricant (thermal), the Newton-Raphson technique is used to solve for pressure and the control volume finite element method is used to solve the energy equation for temperature. This process is repeated until the pressure and temperature reach convergence.

Results of EHD Analysis

The aforementioned EHD analyses were tested in this study over a wide range of operating parameters for both thermal and isothermal conditions. The following sections present the conclusions drawn from these analyses.

Newtonian EHD Analysis

When comparing the isothermal and thermal conditions under heavily loaded lubricated applications, the effect of temperature on the minimum film thickness is significant and cannot be neglected. Varying the speed of the contacting bodies under a constant load shows an increase in surface temperature as the speed is decreased. The introduction of sliding has a significant effect on the minimum film thickness. Holding the applied load and the slip condition constant while reducing the speed results in a higher coefficient of friction. When considering the temperature variation within the lubricant film, the traction force is reduced as the sliding is increased.

Non-Newtonian EHD Analysis

When considering the thermal effects as in the case of the Newtonian fluid model, the slip has a significant effect on the lubricant temperature. Under sliding conditions, the maximum mid-film temperature can be three to four times that of the ambient. For the Eyring fluid model, the effect of slip and temperature on the film thickness is negligible. Under the thermal condition, the coefficient of friction reaches a maximum and then decreases as sliding is increased.

Internal Stresses

Machine components such as bearings, gears, cam and its followers, etc., are frequently subjected to high loads. The high load and high speed application of lubricated rolling/sliding contacts in which the elements elastically deform has a significant effect on the internal stress distributions in the elements, assuming elastic and homogeneous materials. The stress distributions for dry contacts are readily available [16]. However, in EHD lubrication, a film is formed between the elements separating their surfaces. The film thickness modifies the pressure and the internal stress distributions of the rolling/sliding elements. The interface of rolling/sliding elements supports the load and allows the relative motion to take place.

Hertz [17] was the first to investigate the stress distributions in dry contact. Thomas and Hoersch [18] in 1930 calculated stresses for varying depths below the contact surface of two spheres. Balajef [19] calculated the stresses at any point in the half space in elliptical coordinates. Foeppl [20] in 1936 presented a solution to the problem of a cylinder and a spherical ball on a flat plate, and verified the results by photoelastic experiments. Lundberg and Palmgren [21] in 1947 developed the fundamental theory for rolling contact fatigue. This theory is based on the assumption that failure is in the form of shallow pitting and is related to subsurface shearing stresses in the rolling elements. Poritsky [22] in 1949 presented a solution to stresses due to tangential and normal loads on an elastic solid. He used a coefficient of friction of 0.3 in his analysis. Smith and Liu [23] in 1952 also presented results for stresses due to tangential and normal loads. They used a coefficient of friction of 1/3 and extended their analysis to study the significance of these stresses in causing failure by inelastic yielding and fatigue. Dowson, et al., [24] in 1963 studied the stress distribution in lubricated rolling contacts. However, the load considered was extremely low and traction force was neglected. Hamilton and Goodman [25] in 1966 developed a theory for circular sliding contacts. Kuznetsov [26] studied the influence of friction on contact stress, but not on the internal stress field under slip conditions. Bryant [27] presented a closed form solution for the stresses in crowned cylinders based on the Hertzian pressure distribution for the normal pressure and surface shear stress. Kannel and Tevaarwerk [28] in 1983 evaluated subsurface stresses under rolling/sliding contacts. However, they use the Hertzian pressure distribution to calculate the internal stress distributions. Broszeit and Zwirlein [29] studied internal stresses and their influence on material stresses in Hertzian contact.

Many investigators have proposed nonlinear rheological models [30-35] for lubricants under high pressure and high slip conditions. The models have been developed to reduce the large discrepancies that exist between experimental traction data and the numerical results. Conry [36], and Jacobson [37], modified the Reynolds equation to study the non-Newtonian fluid effects on pressure and film thickness in elastohydrodynamic lubricants. Wang and Zhang [9] developed a modified non-Newtonian Reynolds equation based on the shear stress model proposed by Trachman and Cheng [38]. This model allows for the nonlinear character of the lubricants, and has been shown [9] to be in good agreement with Bair and Winer's expression [31].

Even though these references [16-29] addressed the internal stresses problem, a solution which is based on the full EHD solution with the rolling/sliding forces included has not been developed. Sadeghi and Sui [39] developed a numerical solution to the problem of internal stresses in EHD lubrication of rolling/sliding contacts. The Reynolds and elasticity equations are simultaneously solved using the Newton-Raphson technique to obtain the pressure distribution. The pressure distribution is used to obtain the sliding friction force, coefficient of friction, and shear stress on the surface. The pressure distribution and surface shear stress are then used to obtain subsurface normal and shear stress distributions. Stress invariants are employed to obtain the principal normal stresses and the maximum shear stress distributions.

Results of Internal Stress Analysis

Under pure rolling conditions the maximum shear stress in general occurs at 0.78b (where b is the half Hertzian width of contact) below the surface. Traction has a significant effect on the depth at which the maximum shear stress occurs. For low loads, the higher the speed, the closer to the surface the maximum shear stress occurs. For high loads, slip draws the maximum shear stress closer to the surface. The point of stress concentration occurs near the exit zone under low load conditions; however, as the load is increased, this point moves toward the center of contact.

INTERACTIVE COMPUTER GRAPHICS IN ELASTOHYDRODYNAMIC LUBRICATION ANALYSIS

An interactive computer graphics package has been developed for use in the design and analysis of Elastohydrodynamic (EHD) lubrication of rolling/sliding machine elements. The package contains the following: 1) set-up of initial values including operating conditions, material properties, and lubricant properties; 2) execution of one of six EHD analysis programs and calculation of shear stresses within the solids; and 3) viewing the generated results including film thickness, pressure, temperature, and internal stresses. This software was developed for use on Sun Workstations using X-Windows developed at MIT and the graphics package developed by the CADLAB at Purdue University. However, the software developed can be executed on any computer which can simulate X-windows. This software and the individual programs which the software runs on was developed using the FORTRAN computer language. Therefore, if the X-Windows software is not available the programs can be individually complied and executed.The Tribology Laboratory will provide the graphics package developed by the CADLAB.

Introduction

Complete understanding of heavily loaded lubricated rolling/sliding machine components such as bearings, gears, etc., is of significant importance. The study of heavily loaded lubricated rolling/sliding contacts (Elastohydrodynamic, EHD) has been investigated extensively in recent years. Sadeghi and Sui have developed several models to analyze the Elastohydrodynamic lubrication for Newtonian and non-Newtonian fluid models under isothermal and thermal conditions. The operating parameters that significantly effect the performance of heavily loaded lubricated contacts are the load, speed, slip, and material parameter. The models allow the EHD lubrication of line contacts to be fully investigated. They provide knowledge of film thickness, pressure, and temperature within the lubricant film and the location and magnitude of mechanical and thermal stresses within the rolling/sliding elements.

One of the major problems in EHD analysis is inputting the operating conditions, and material and lubricant properties. This is especially difficult because of the large number of input variables. Originally two methods for setting up the input variables were used. The input data files for each case of interest were created, and particular values within the program were changed and the program was compiled. These procedures are very time consuming and difficult to use. To view the output data (results), separate programs were used which accessed plotting packages for a particular work station that had graphics capability. Ultimately, the analysis of one EHD condition resulted in the user performing three tasks.

Creating an interactive computer aided design and graphics package has reduced the complexity and the difficulty associated with analyzing and understanding EHD lubrication. Now, the set-up of initial conditions is accomplished easily by interactive events such as choosing menu items and selecting items with the mouse button; both of which result in the user being prompted to enter a new value via the keyboard. All EHD analyses and stress calculations are accomplished by choosing menu items and entering the desired file name for storing the generated data. Finally, the data can be viewed in one of several manners again by choosing the appropriate menu item. With this interactive approach, the user has all of the tools necessary for performing an Elastohydrodynamic lubrication analysis with little difficulty.

Introduction to Interactive Computer Graphics

Computers have become very powerful tools in our world today. With the existing technology, computer tools have been shown to be a fast and efficient means to an end. For example, in industry computers are being used to monitor inventory (Just in time, JIT), run simple and complex processes (Computer Integrated Manufacturing, CIM), and design and analyze machine components, products, etc. (Computer Aided Design, CAD). Because of their power and efficiency, computers have become a necessity in the design process.

With the advent of interactive computer graphics, pictorial representations have become the medium through which the designer interacts with the computer. "Pictorial communication is a medium that is both natural and efficient to human beings and yet is sufficiently precise for computer manipulation. Most people enjoy interacting graphically more than they do the more traditional and more limited alphanumeric communication techniques. Interactive graphics can be used to understand complex phenomena, to design technological artifacts, and to amuse-it is an extremely versatile, aesthetically pleasing and instructive medium" [40].

With the use of traditional numerical methods programs, the user is at the mercy of the programmer when setting up and running the program. During execution, the user often sits idly by, unsure whether the computer is performing the task desired. Upon completion, the user must determine a way to analyze the generated data in a way that is meaningful. With the use of interactive computer graphics, the user is given a pictorial representation of the problem being analyzed which gives the confidence that the correct value is being assigned to the correct variable. Upon completion of the analysis, the user can examine the generated data graphically (often with the use of color) through the use of line plots, contour plots, solid models, etc. In all, the user has a powerful design tool with relatively little user burden which greatly reduces the lengthy design iterations and detailed hand drawings of the past.

Features of the Graphics Package

This section describes the many features of the graphics package with full color pictures illustrating the features.

Description of the Package

Upon start-up of the graphics package, the user is given an introduction to the package and its purpose. "Page 1" (Figure 1) welcomes the user to the EHD Simulator which was developed at *Purdue University in the Tribology Laboratory.* "Page 2" (Figure 2) describes the concept of Elastohydrodynamic lubrication and provides three applicable examples: a roller bearing, a cam and its follower, and two mating gear teeth.

Set-up of Operating Conditions

Once the introduction is completed, the main variable declaration page appears. This page (Figure 3) consists of a view of two cylinders in contact separated by a lubricant film, six pull-down menus, and three boxes indicating the types of units that can be used (metric, English, and non-dimensional) in the manipulation of the Elastohydrodynamic lubrication programs.

Choosing Units

Before execution can continue, the type of units to be used must be chosen. Once the units have been chosen, the selected box is highlighted (Figure 4) and the units can not be changed until the package is terminated and started over. With the units selected, the execution continues to allow the initialization of operating conditions, material properties, etc. A dialog is displayed describing the procedure for changing the appropriate values.

Loading Conditions

The view of the two cylinders in contact (Figure 4) contains arrows indicating the applied load, the speed of each cylinder, and the equivalent radius of contact for each cylinder. The values of these variables can be shown (and changed) by selecting the appropriate arrow with the mouse cursor and pressing the mouse button. In all cases, the chosen arrow is highlighted and a prompt is displayed (Figure 5) allowing the user to change the value.

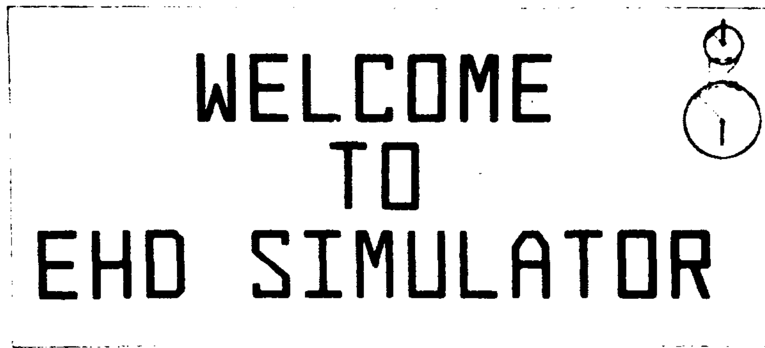

Figure 1. Introduction to the graphics package.

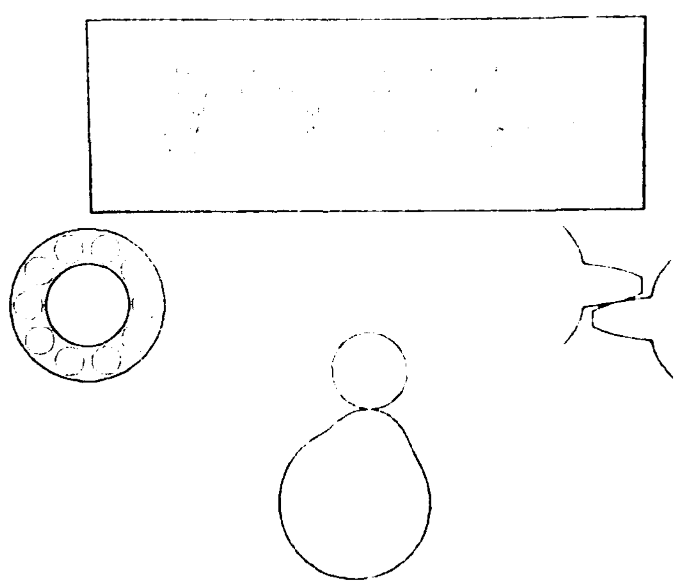

Figure 2. Description of Elastohydrodynamic lubrication.

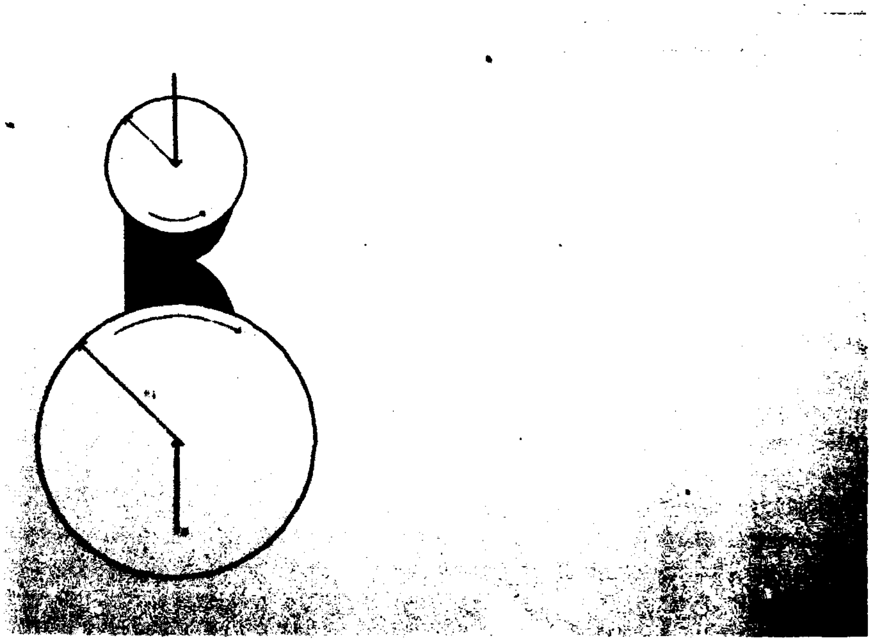

Figure 3. Variable declaration page.

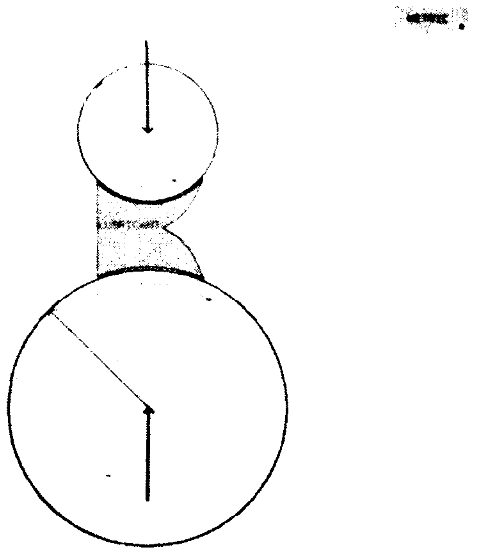

Figure 4. Selecting the type of units.

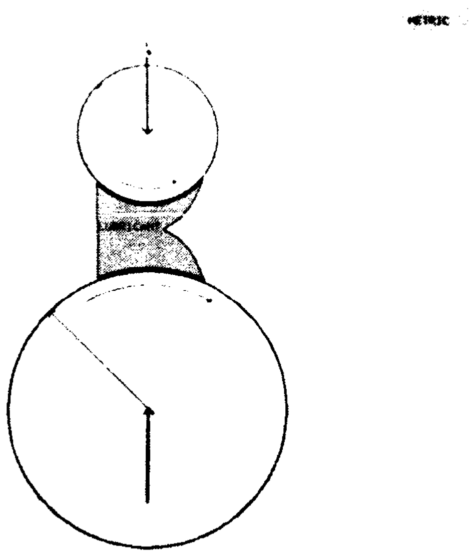

Figure 5. Setting up the loading conditions.

Material Properties

Each cylinder in Figure 4 has properties inherent to it. These properties describe the type of material being used. To view these properties (and change them), the cursor is positioned within the cylinder and the mouse button is pressed. The cylinder is highlighted and a list of the current material properties is displayed (Figure 6). To change any of these properties, the mouse cursor must be positioned anywhere along the property description and the mouse button pressed. A prompt is displayed (Figure 7) allowing the user to change the current value. When all changes have been made, they may be saved or cancelled by selecting the appropriate box (SAVE or CANCEL, respectively). If the "SAVE" box is chosen, all changes are saved for use in the EHD analysis and the values are retained until they are changed again. If the "CANCEL" box is chosen, all changes are disregarded and the variables retain their previous values.

Lubricant Properties

Each lubricant has properties inherent to it. These values are stored in data files under the lubricant name in the users directory. To choose a particular lubricant and view/change its properties, the mouse cursor must be positioned within the lubricant area as shown in Figure 8 and the mouse button must be pressed. This results in a list of the types of lubricants that can be used - Newtonian or non-Newtonian (Figure 9). The particular type is chosen by positioning the mouse cursor within the appropriate box and pressing the mouse button. A list of current lubricant names is displayed (Figure 10) along with a box named OTHER. One of the existing lubricants can be selected by choosing the particular box or a new lubricant can be defined by choosing "OTHER". In all cases, the list of the lubricant properties along with their current values is displayed (Figure 11). To change any of these properties, the mouse cursor must be positioned anywhere along the property description and the mouse button must be pressed. A prompt is displayed (in the same manner as the material properties - Figure 7) allowing the user to change the current value. When all changes have been made, they may be saved or cancelled by selecting the appropriate box (SAVE or CANCEL, respectively). If the "SAVE" box is chosen, all changes are saved for use in the EHD analysis and they retain these values until they are changed again. If the "CANCEL" box is chosen, all changes are disregarded and the variables retain their previous values. Only after the lubricant has been defined can the EHD analysis be performed.

Initial Guesses and Grid Definition

As discussed in previously, the EHD analysis programs use the Newton-Raphson numerical method to solve for the film thickness and pressure within the lubricant and the control volume finite element method to solve for the temperature distribution within the lubricant. In performing these methods, certain initial guesses must be made to ensure convergence. The default values have been chosen after numerous applications of the EHD analyses and they have proved to provide accurate and efficient convergence. These values have been placed in the second menu command entitled "Initial Guesses" (Figure 12); only the experienced EHD designer who fully understands and is familiar with the numerical methods should attempt to change these values. The last item in this menu list, plot flag, is used for plotting each iteration of the Newton-Raphson scheme. Plotting each iteration can be a very useful tool in determining whether the solution will converge and is normally only used by the experienced designer.

In the "Grid Definition" menu (Figure 13), the size of the grid is specified. This menu allows the user to define the total number of nodal points (for control volume method) along the rolling direction, across the lubricant, and into the solid as well as the starting and ending point of the mesh.

To change any of these variables, the menu command must be selected and the mouse cursor must be drug down the list until the particular item is highlighted as shown in Figure 12. Upon releasing the mouse button, a prompt is displayed (Figure 14) allowing the user to change the current value. Once the value has been entered, it is stored for future use in the EHD analysis.

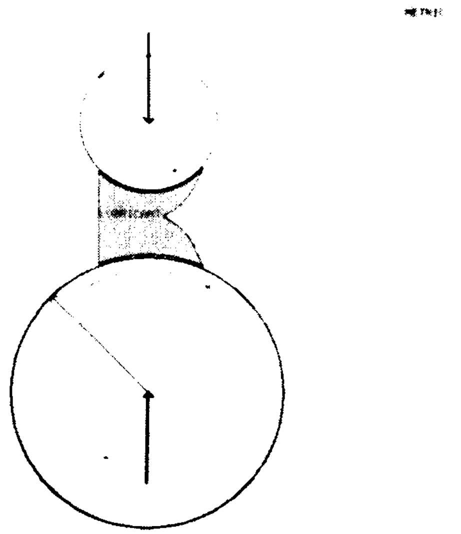

Figure 6. Listing of the material properties.

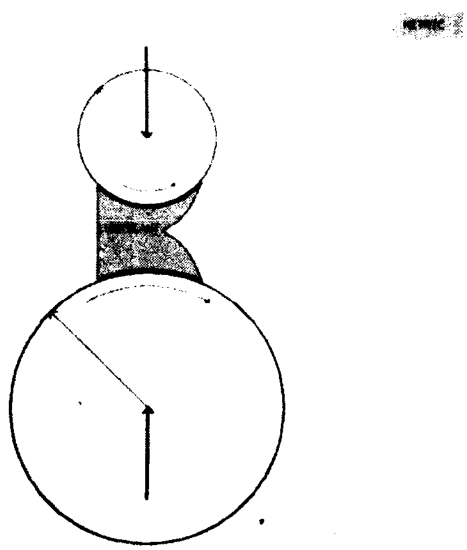

Figure 7. Changing the material properties.

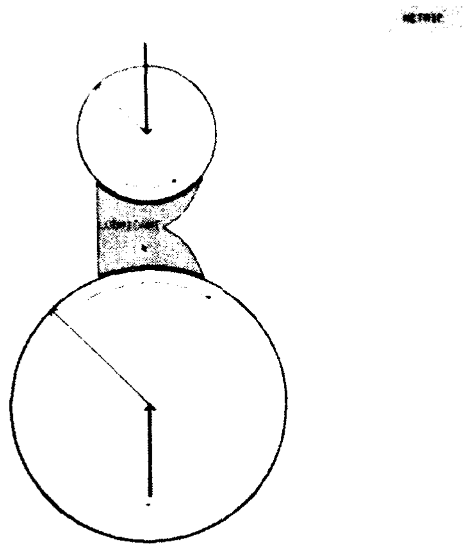

Figure 8. Selecting a lubricant.

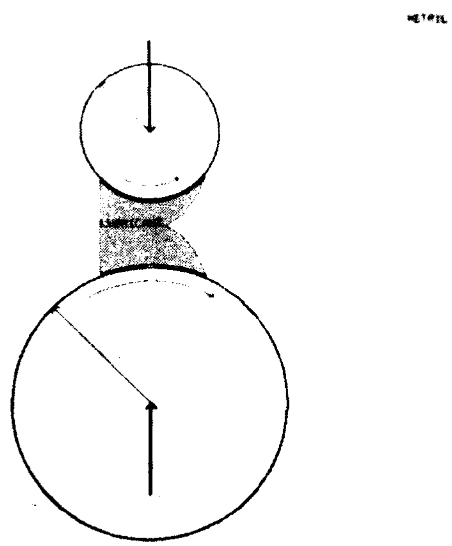

Figure 9. Listing of the lubricant types.

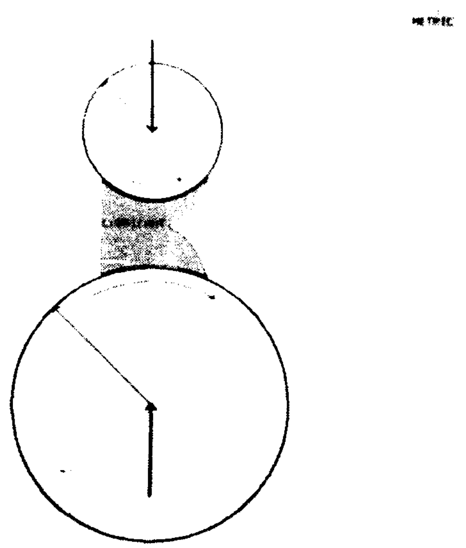

Figure 10. Listing of the lubricant names.

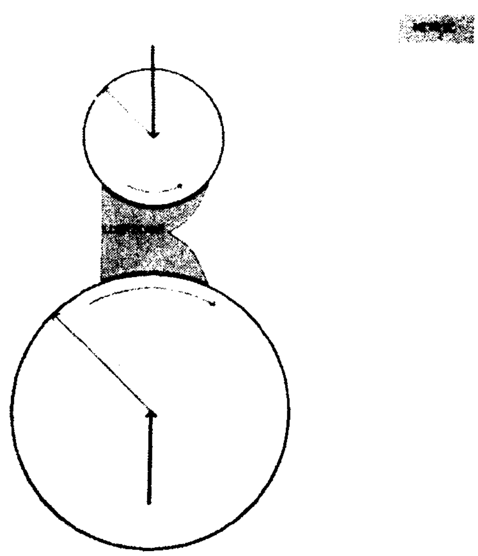

Figure 11. Listing of the lubricant properties.

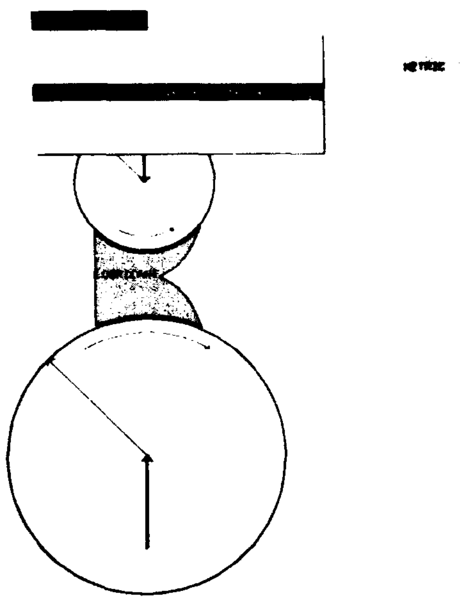

Figure 12. Contents of the Initial Guesses menu.

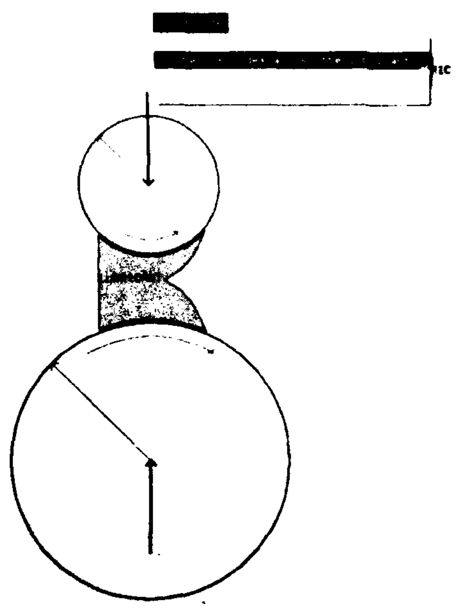

Figure 13. Contents of the Grid Definition menu.

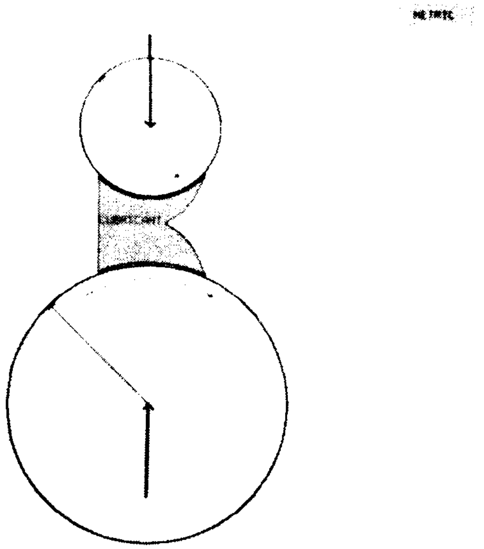

Figure 14. Changing a variable from a menu list.

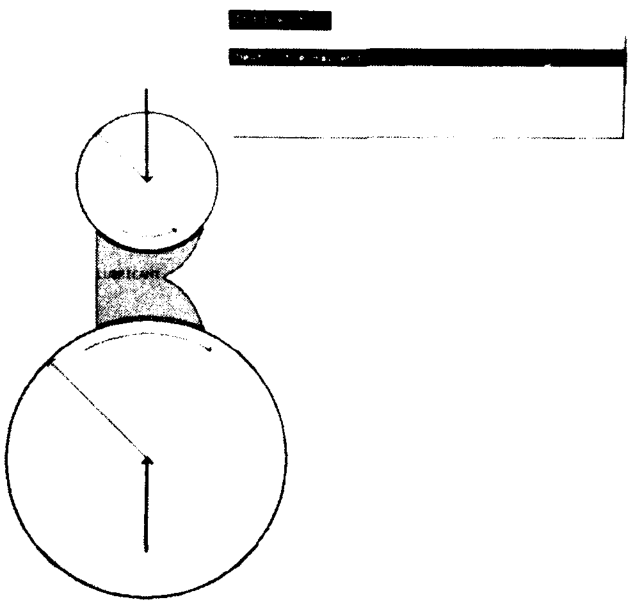

Figure 15. Contents of the EHD Analysis menu.

EHD Analysis

The fourth menu item entitled "EHD Analysis" contains the six EHD analysis models available (Figure 15). This menu item is initially disabled (see Figure 4) until a lubricant is chosen which indicates which EHD model is to be used. Only the models corresponding to the type of lubricant chosen (ie. Newtonian model) are enabled. To perform one of these analyses, the appropriate item from the "EHD Analysis" menu must be chosen with the mouse cursor. A prompt is then displayed for entering the file name to store the generated data which allows each analysis to be stored in separate files (Figure 16). Next, a prompt is displayed for entering the file name for storing the velocity data if a thermal EHD analysis is to be performed (Figure 17). At this point, an object file corresponding to the chosen EHD model is compiled (Figure 18) and the resulting executable is run using the predefined variables (Figure 19). While the analysis is being performed, no other action will take place unless the plot flag (see "Initial Guesses and Grid Definition") has been turned on. When the user chooses to plot each iteration , a new window is created containing a view of the current film thickness and pressure profile (Figure 20). This window appears for a set period of time and is then disposed of and execution continues. At the conclusion of the analysis, the original variable declaration page is displayed and the menu item corresponding to the EHD analysis just performed is disabled (Figure 21). This feature prevents the user from performing the same analysis with the same data. In order to perform the same EHD analysis with different data, the lubricant selection process must be repeated for each case. Now, the menu item for viewing the film thickness and pressure is enabled in the View Results menu command (Figure 22) and if a thermal analysis was chosen, the temperature distribution and velocity profile can also be viewed (see Viewing the Results). Other options include performing another EHD Analysis and computing the internal stresses (see Stress Calculation Within Solid).

Stress Calculation Within a Solid

The fifth menu item entitled "Stress Calculation" contains the items for calculating the maximum internal mechanical and thermal shear stresses within the solids (Figure 23). This menu item is initially disabled (see Figure 4) until an EHD analysis is performed. After an EHD analysis has been performed, this menu command is enabled along with the Mechanical Stress item and the Thermal Stress item (if a thermal EHD analysis has been performed). To perform one of these analyses, the appropriate item must be chosen with the mouse cursor. A prompt is then displayed for entering the EHD data file name (with the default file name being the most recently created EHD data file) to be used in the calculation (Figure 24) followed by a prompt for entering the file name to store the generated stress data which allows each analysis to be stored in separate files(Figure 25). When entering the EHD data file to be used, if there is no file with the given name in the user's current directory an error prompt is displayed indicating that the file does not exist (Figure 26) and a new file name must be entered. After entering the EHD output file name and the mechanical stress output file name, an object file corresponding to the chosen menu item is compiled and the resulting executable is run (as in performing an EHD analysis). At the conclusion of the analysis, the original variable declaration page is displayed and the menu item corresponding to the analysis performed is disabled until another EHD analysis is performed. This feature prevents the user from performing the same analysis with the same data. Now, the calculated stresses can be viewed (see Viewing the Results) or another EHD analysis can be performed.

Viewing the Results

The sixth menu item entitled "View Results" is used for displaying the generated data from the EHD analyses and stress calculations. This menu item is initially disabled (see Figure 4) until the corresponding analyses are performed. To view any of the results, the appropriate menu item must be chosen with the mouse cursor (Figure 27). A prompt for entering the type of units for viewing the results in is displayed (Figure 28). This feature allows the user to view the results in

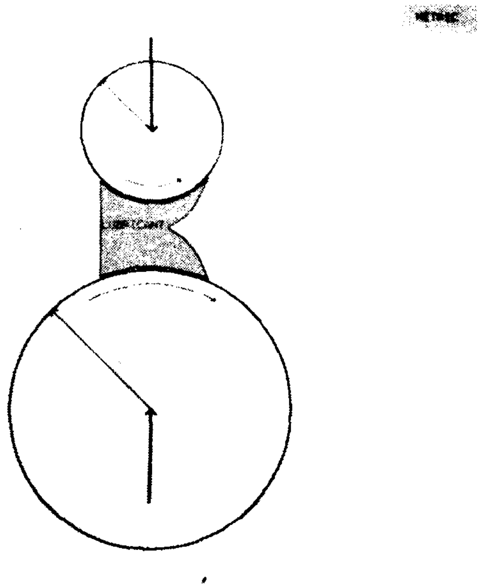

Figure 16. Entering an EHD output data file name.

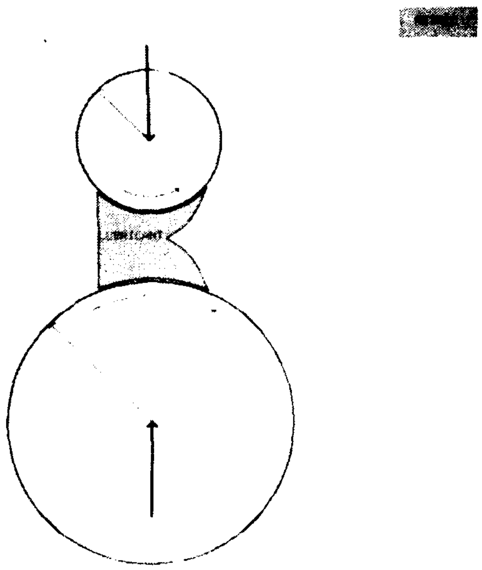

Figure 17. Entering a velocity output data file name.

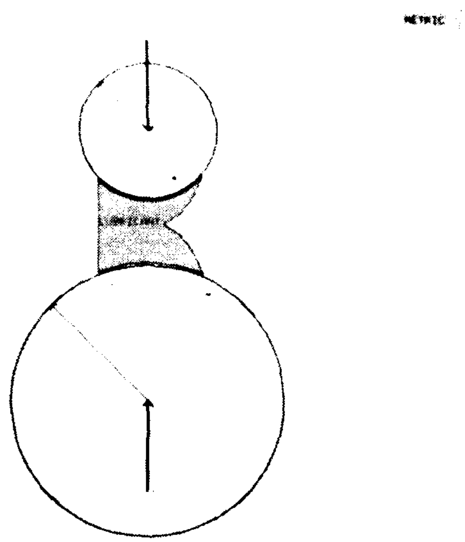

Figure 18. Prompt indicating a program is compiling.

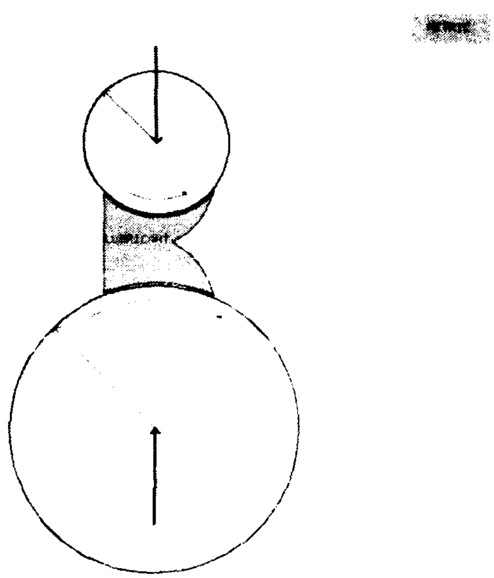

Figure 19. Prompt indicating a program is executing.

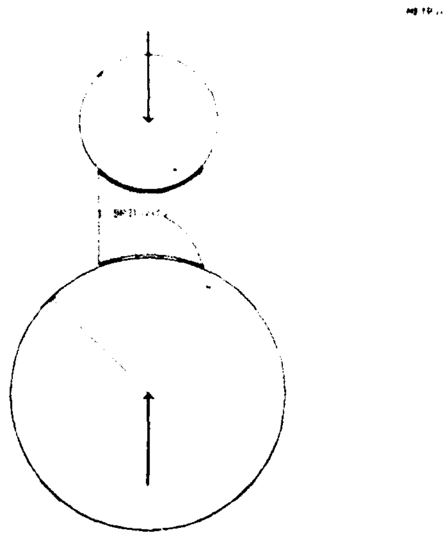

Figure 20. Plotting each iteration of the Newton-Raphson technique.

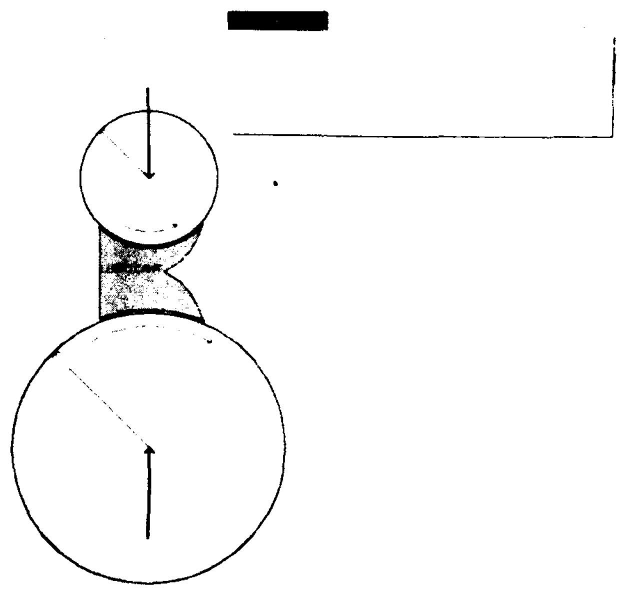

Figure 21. Contents of the EHD Analysis menu after an EHD analysis has been performed.

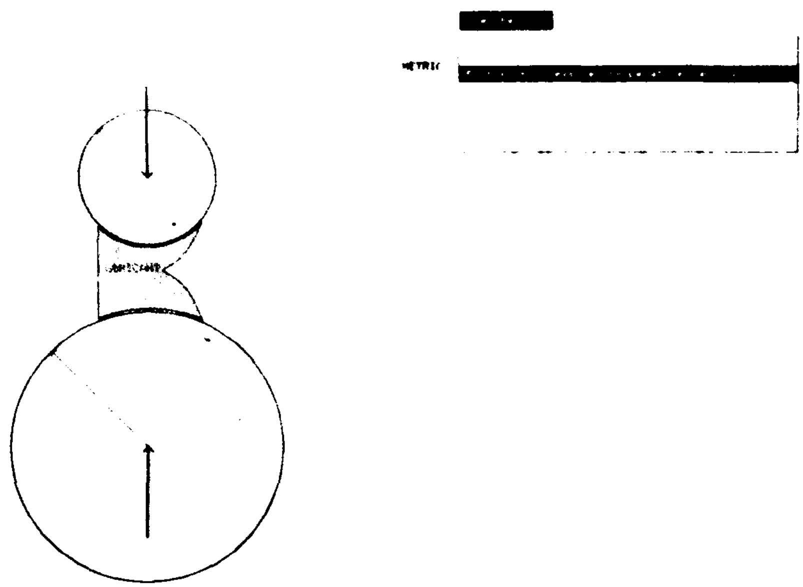

Figure 22. Contents of the View Results menu after an EHD analysis has been performed.

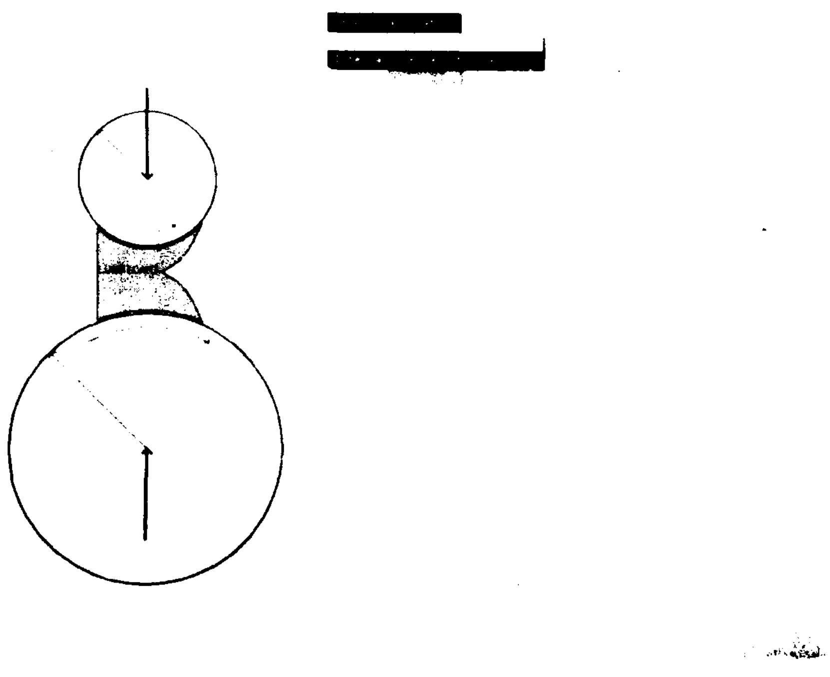

Figure 23. Contents of the Stress Calculation menu.

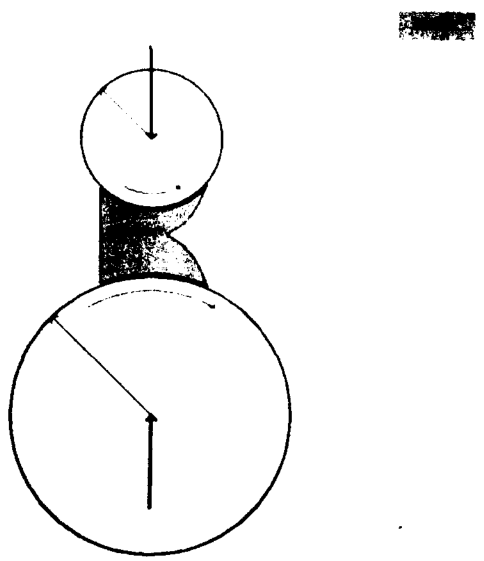

Figure 24. Entering an EHD file name to be used in the stress calculation.

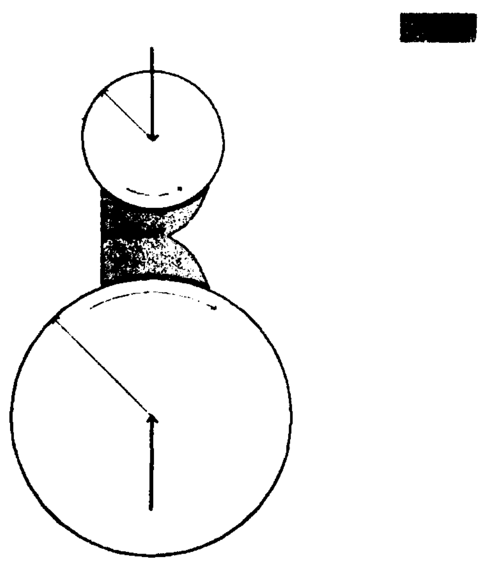

Figure 25. Entering a stress output data file name.

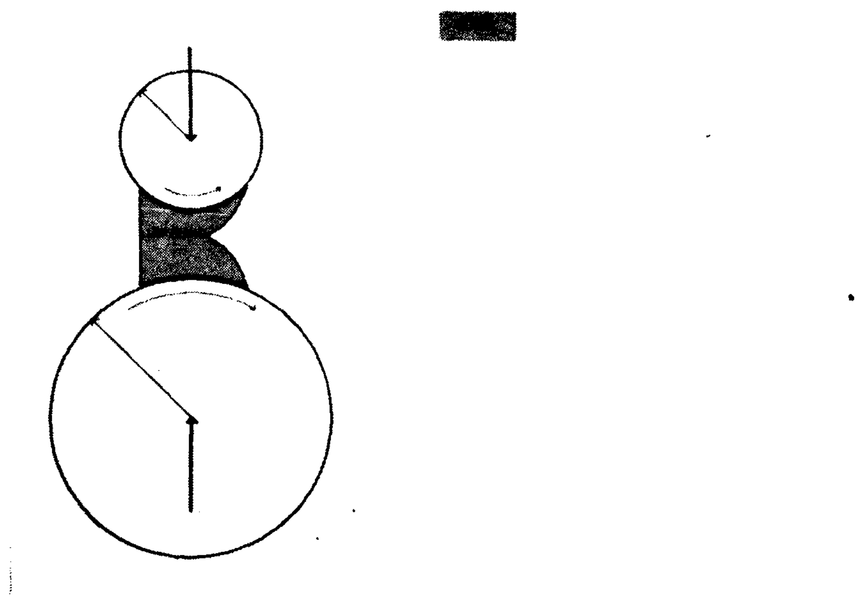

Figure 26. Error prompt for a non-existing data file name.

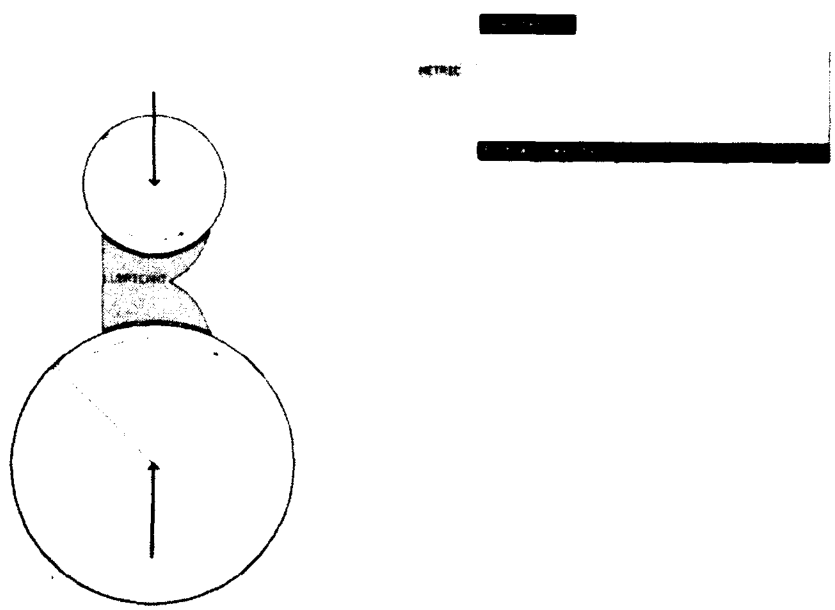

Figure 27. Choosing an item from the View Results menu.

either metric (m), English (e), or non-dimensional (n) irrespective of the units used in the analysis. Following this, prompts are displayed for entering the necessary data file names (with the default file names being the most recently created files). For example, if the item for viewing the film thickness, pressure, and temperature is chosen, a prompt for entering the EHD data file name is displayed(Figure 29). When entering these data file names, if there is no file with the given name in the user's directory, an error prompt is displayed indicating that the file does not exist and a new file name must be entered. After entering all of the necessary information, an object file is compiled and the executable is run resulting in a new window being created with the chosen view displayed (Figure 30). The display consists of a view of the data (line plots and/or color profiles) and a color grid indicating the values corresponding to the colors in the profiles. A special feature of this display allows the user to examine the value at any location within a particular profile. This is accomplished by moving the mouse cursor to any position within a profile and pressing one of the mouse buttons. The location is then displayed along with the corresponding value (temperature, pressure, or stress) at that location (Figure 31). Another feature allows the user to view multiple files at the same time. This option can only be used when viewing a single "item" (ie. not when performing a comprehensive plot). To perform a multiple view, the menu command entitled "Multiple Views" is used (Figure 32). The user selects the menu item "Another View" and is prompted to enter the necessary file name (Figure 33). This option can be used a maximum of four times which allows the user to compare four different situations at the same time to analyze the effects of varying a certain operating parameter (ie. applied load) or using different lubricants or materials (Figure 34). To terminate the display, the menu command (in the display window) entitled "Quit" with only a single menu item is chosen (Figure 35) and the window is disposed of returning the user to the original variable declaration page. At this point, a "complete" EHD analysis has been performed and the user can start over or terminate execution of the graphics package.

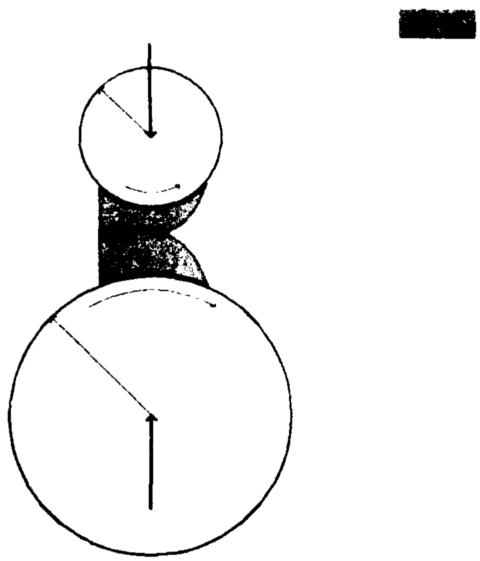

Figure 28. Entering the type of units for viewing the generated data.

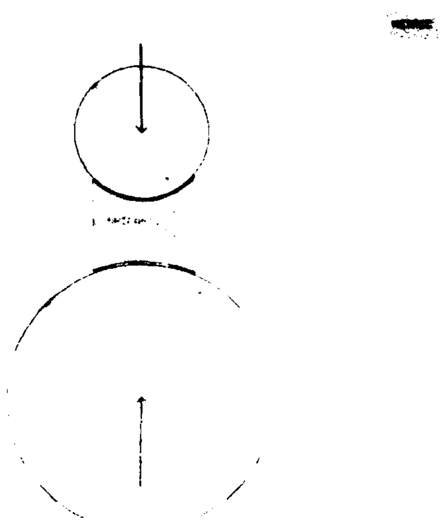

Figure 29. Entering a data file name to be viewed.

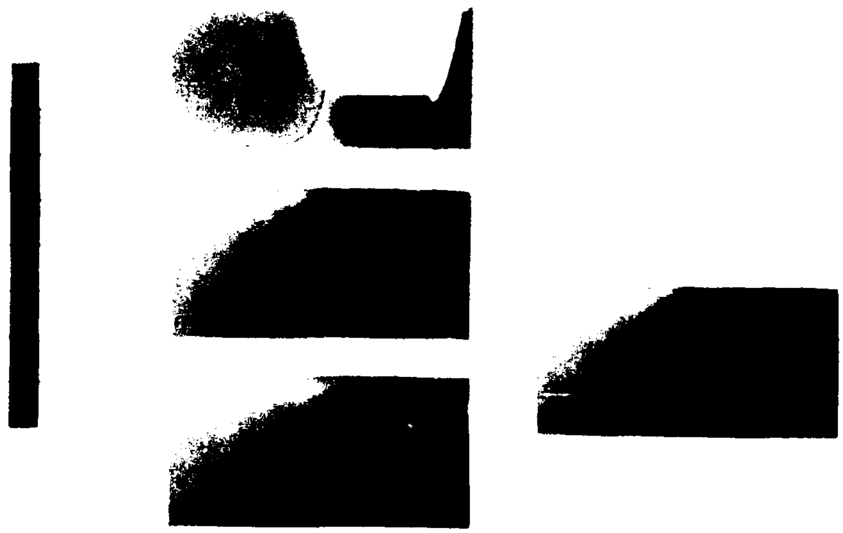

Figure 30. Comprehensive view of a complete analysis.

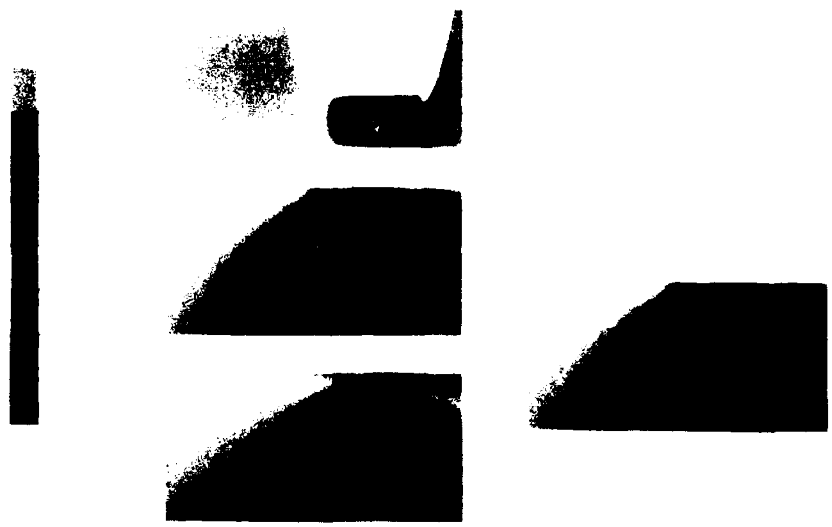

Figure 31. Indication of values at a particular location within a profile.

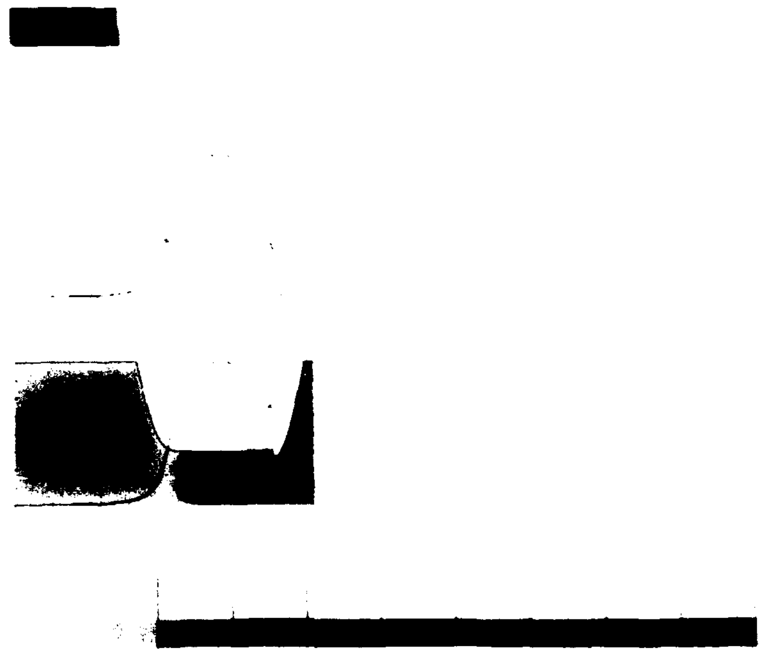

Figure 32.   Creating multiple views using the Multiple View menu.

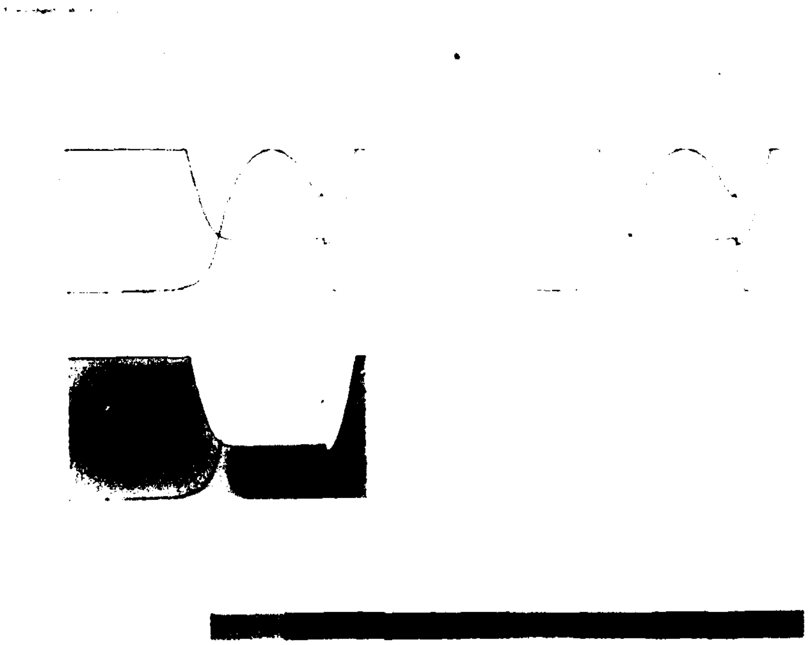

Figure 33.   Entering a new data file name for a multiple view.

Figure ^+ Multiple views of film thickness, pressure, and temperature.

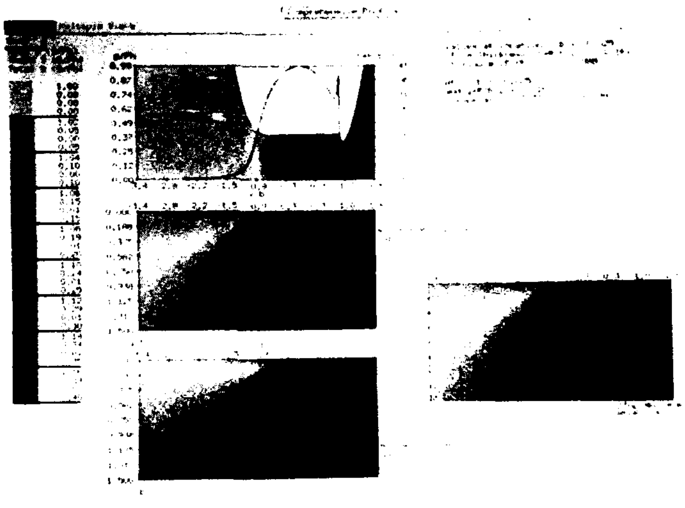

Figure 35. Terminating the current view.

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APPENDIX-A USERS'S MANUAL

INSTALLATION OF THE GRAPHICS PACKAGE

1. Contents of the Graphics Package

With the initial installation of the interactive computer graphics package, the following files should be present:

1.1. Executables

1) setup* - This is the main executable which runs the entire graphics package. To begin execution, type the word "setup" at the unix prompt and follow the instructions provided.

1.2. Object Files

These files are the pre-compiled versions of the executables. They are compiled by the main executable (setup*) when chosen or they can be compiled independently. When these files are used independent of the package, they must be handled in a manner discussed in Chapter AIII-Independent Analysis. These files are very important in that they are necessary for the EHD analyses, stress calculations, etc. They should be immediately backed up under another name because if they are lost, there is no way of creating new files.

1) newton.ehd.hold - EHD analysis based on the Newtonian fluid model. When compiled, this file becomes an executable which can be used to perform either the isothermal or thermal case.
2) hyper.ehd.hold - EHD analysis based on the non-Newtonian hyperbolic fluid model. When compiled, this file becomes an executable which can be used to perform only the isothermal case.
3) eyring1.ehd.hold - EHD analysis based on the non-Newtonian Re-Eyring fluid model. When compiled, this file becomes an executable which can be used to perform either the isothermal or thermal case.
4) eyring2.ehd.hold - EHD analysis based on the non-Newtonian Re-Eyring fluid model with additional consideration of the thermal expansion of the solids. When compiled, this file becomes an executable which uses the results from the thermal case of eyring1.ehd.hold.
5) mechstress.hold - Analysis performed on the contacting solids using the results generated from the EHD analysis. When compiled, this file becomes an executable which calculates the maximum internal mechanical shear stresses based on the loading conditions and the film thickness and pressure within the lubricant.
6) thermstress.hold - Analysis performed on the contacting solids using the results generated only from thermal EHD analyses. When compiled, this file becomes an executable which calculates the maximum internal thermal shear stresses based on the temperature distribution within the lubricant film.
7) plot.hold - Used to view the generated results from the previous analyses. There are five possible views and they are discussed in Chapter AII - section 5.
8) graph.hold - Used in conjunction with the EHD analysis to plot the film thickness and pressure within the lubricant after each iteration of the Newton-Raphson technique.

1.3. Source Code

The following two items are the actual coded programs that make up the interactive graphics package:

1) setup.F - This is the source code for the main executable setup*. This code has been provided in the event some changes are desired to be made (ie. taking out "Pages 1 and 2). Care should be taken when making changes to the source code. With this

in mind, keep a copy of the original source code and make changes to a separate copy.

2) plot.F - This is the source code for the routine that displays the generated data. This code has been provided for the same reasons as setup.F and the same suggestions apply to this source code.

1.4. Lubricant Data Files

This package comes with two lubricant data files. This can be expanded to create a data base of lubricants (explained in Chapter AII - section 3.3.). The lubricant files provided are for mineral and parafinic oils and they contain the basic properties inherent to each lubricant.

1.5. Extra Files

The remaining files are for aesthetic display purposes. When listing the contents of the directory with the "ls" command, these files do not appear; however, when using the "ls -a" command, they will be listed with all of the other files.

1) .bearing - This file contains the geometry defining a two-dimensional roller bearing for use on "Page 2" of the introduction during execution of "setup*."
2) .cam - This file contains the geometry defining a two-dimensional cam for use on "Page 2" of the introduction during execution of "setup*."
3) .follower - This file contains the geometry defining a two-dimensional cylindrical follower for use on "Page 2" of the introduction during execution of "setup*."
4) .gear - This file contains the geometry defining a two-dimensional view of two gear teeth in mesh for use on "Page 2" of the introduction during execution of "setup*."
5) .grif - This file contains the geometry defining a two-dimensional view of the Purdue emblem, the griffin, for use on "Page 1" of the introduction during execution of "setup*."

These files can be bypassed by commenting out the following coded line located on line number 56 in setup.F.

```
call Intro(wid,pixel1,pixel2,pixel3,pixel4,iconflag)
```

2. Compilation and Execution

Once all of the files for the graphics package have been loaded, there is only one command that needs to be issued. This command (shown below) begins the execution of the graphics package which then proceeds by the use of interactive events such as mouse button clicks and menu item selections. At the unix prompt, type in the following command:

```
> setup
```

followed by a keyboard return (or enter).

2.1. Compilation of Graphics Code

In the event that changes have been made to one of the ".F" files (graphics source code) or for some other reason the program(s) needs to be re-compiled, the following unix command must be used at the unix prompt:

> f77 (-f68881) **filename**.F -lfgrafic -lX11

where **filename** can be either "setup" or "plot." The "-f68881" flag needs to be used on Sun workstations that require a floating point specifier. This applies to Sun 3 but not to Sun 4 machines.

2.2. Compilation of Object Files

In the event that the EHD analyses, stress calculations, and/or viewing of the results is desired to be performed independently, the object file must be compiled. Because different programs use different methods, there are a few variations to the compilation command. In all cases, **copy** (do not move) the ".hold" file of interest to a ".o" file and follow the descriptions below:

1) For newton.ehd.o, hyper.ehd.o, eyring2.ehd.o, mechstress.o, and thermstress.o, the following unix command must be used at the unix prompt:

   > f77 (-f68881) **filename**.o

   where **filename** corresponds to one of the above titles and the "-f68881" flag is needed only on machines requiring a floating point specifier.

2) For eyring1.ehd.o, the following unix command must be used at the unix prompt:

   > f77 (-f68881) eyring1.ehd.o -limslib -lm

   where the flag "-limslib" links the IMSL routines used in the program, the flag "-lm" links the math library, and the flag "-f68881" is needed only on machines requiring a floating point specifier.

3) For plot.o and graph.o*, the following unix command must be used at the unix prompt:

   > f77 (-f68881) **filename**.o -lfgrafic -lX11

   where **filename** corresponds to "plot" or "graph," the "-lX11" flag is used to link the X Window Manager, the "-lfgrafic" flag is used to link the CADLAB Graphics subroutines, and the "-f68881" flag is needed only on machines requiring a floating point specifier.

* There should be no reason to compile graph.o as this file is used only in viewing each iteration of the Newton-Raphson scheme in the EHD analysis.

RUNNING THE GRAPHICS PACKAGE

This section describes the basic features involved in running the main executable setup*. To begin execution, type the command "setup" at the unix prompt as described in Chapter AI - section 2.

1. Pages 1 and 2

The first two "pages" of the main executable setup* serve as an introduction to the graphics package and a description of the type of analysis to be performed. "Page 1" welcomes the user to the EHD Simulator which was developed at Purdue University in the Tribology Laboratory. Also included is a view of the Purdue emblem - the griffin. To continue on to "Page 2," the mouse cursor must be positioned within the "CONTINUE" box and one of the mouse buttons must be pressed.

"Page 2" describes the concept of Elastohydrodynamic (EHD) lubrication and provides three applicable examples: 1) a roller-bearing; 2) a cam and its follower; and 3) two gear teeth in mesh. To continue on to the main variable declaration page, the mouse cursor must be positioned within the "CONTINUE" box and one of the mouse buttons must be pressed. These pages serve only as an introduction to the package and have no effect on the remaining execution.

2. Set Up of Operating Conditions

Once the introduction is completed, the main variable declaration page appears. This page consists of a view of two cylinders in contact separated by a lubricant film, six pull-down menus, and three boxes indicating the types of units that can be used (metric, English, and non-dimensional).

2.1. Choosing Units

Before execution can continue, the type of units to be used must be chosen by positioning the mouse cursor in one of the units boxes and pressing one of the mouse buttons. Once the units have been chosen, the selected box is highlighted and they cannot be changed until the main executable setup* is terminated and restarted. With the units selected, the execution continues to allow changing the loading conditions, material properties, etc. A dialog is displayed describing the procedure for changing the values and three of the menus (stop, initial guesses, and grid definition) become enabled.

2.2. Loading Conditions

The view of the two cylinders in contact contains arrows indicating the applied load W, the speed of each cylinder U1 and U2, and the radius of each cylinder R1 and R2. To change any of these variables, the mouse cursor must be positioned anywhere along the respective arrow and one of the mouse buttons must be pressed. In all cases, the chosen arrow is highlighted with red and a prompt indicating the parameter chosen, the current value (with correct units), and a box for entering the new value is displayed. At this point, a new value can be entered from the keyboard followed by a keyboard return resulting in the changing of the variable or the default value can be retained with just the keyboard return. After the keyboard return, the prompt disappears and the arrow is returned to its original color. When working in non-dimensional units, selecting the speed arrows provides a prompt for entering the dimensionless speed parameter. After the speed is entered, another prompt for entering the percent slip between the cylinders is displayed. This prompt is handled in the same manner described previously.

2.3. Material Properties

Each cylinder has properties inherent to it. To change any or all of these properties, the mouse cursor must be positioned anywhere within the cylinder (except along the arrows) and one of the mouse buttons must be pressed. After this, the circumference of the cylinder is highlighted in red and a list of the following properties is displayed with their current values:

Modulus of Elasticity
Poisson's Ratio
Density
Thermal Conductivity
Specific Heat
Asperity Amplitude
Asperity Radius of Curvature

To change any of these variables, the mouse cursor must be positioned anywhere along the prompt and one of the mouse buttons must be pressed. In all cases, a prompt indicating the chosen variable and a box for entering the new value is displayed beneath the current variable. A new value can be entered from the keyboard followed by a keyboard return resulting in the changing of the variable or the default value can be retained with just the keyboard return. After the keyboard return, the prompt disappears and the new value is displayed in the initial list

When all changes have been made, they may be saved or cancelled by selecting the appropriate box (SAVE or CANCEL, respectively). In either case, the chosen box is highlighted, the list is erased, and the cylinder is returned to its original color. If the "SAVE" box is chosen, all changes are saved for use in future EHD analyses and the variables retain these values until they are changed again. If the "CANCEL" box is chosen, all changes are disregarded and the variables retain their previous values.

2.4. Lubricant Properties

Each lubricant has special properties inherent to it. These values are stored in file names based on the lubricant name which are accessed when the lubricant name is chosen (see Chapter AII - section 3.2.). Once the particular lubricant has been selected for the EHD analysis, a list of the following properties is displayed with their current values:

Lubricant Name
Ambient Viscosity
Ambient Density
Thermal Expansivity
Exponent for Roeland's Viscosity Model
Temperature-Viscosity Coefficient
Inlet Lubricant Temperature
Thermal Conductivity
Specific Heat
Dowson-Higginson Density Model Constant 1
Dowson-Higginson Density Model Constant 2
Pressure Viscosity Exponent
Limiting Shear Stress*
Limiting Shear Stress**
Shear Stress Constant**

* This value is only used when the Eyring fluid model is chosen
** These values are only used when the Hyperbolic fluid model is chosen

To change any of these variables, the mouse cursor must be positioned anywhere along the prompt and one of the mouse buttons must be pressed. In all cases, a prompt indicating the chosen variable and a box for entering the new value is displayed beneath the current variable. A new value can be entered from the keyboard followed by a keyboard return resulting in the changing of the value or the default value can be retained with just the keyboard return. After the keyboard return, the prompt disappears and the new value is displayed in the initial list.

When all changes have been made, they may be saved or cancelled by selecting the appropriate box (SAVE or CANCEL, respectively). In either case, the chosen box is highlighted, the list is erased, and the lubricant box is returned to its original color. If the "CANCEL" box is chosen, all changes are disregarded and the variables retain their previous values. If the "SAVE" box is chosen, all changes are saved for use in future EHD analyses and the variables retain these values until they are changed again. Also, a prompt is displayed asking if the user would like to store these values in a data file for future use (see Chapter AII - section 3.3.)

2.5. Initial Guesses

The EHD analysis is conducted using the Newton-Raphson numerical technique to solve for the film thickness and pressure within the lubricant and the control volume finite element method for the temperature distribution within the lubricant. When implementing the Newton-Raphson technique or the control volume finite element method, certain initial guesses must be made to ensure convergence. The default values have been chosen after numerous applications of the EHD analyses and they have proved to provide accurate and efficient convergence. These values have been placed in the second menu command entitled "Initial Guesses". **Only the experienced EHD designer who fully understands the numerical methods should attempt to change these values**. The following variables are found in "Initial Guesses":

Initial Guess for Exit Nodal Point
Initial Guess for Exit Film Thickness
Dimensionless Film Thickness Constant
Temperature Convergence Criteria
Maximum Number of Iterations for Newton-Raphson Technique
Maximum Number of Iterations for Control Volume Method
Plot Flag

The last item in this list, Plot Flag, is used for plotting each iteration of the Newton-Raphson technique. Plotting each iteration can be very useful in determining whether the solution will converge and is normally only used by the experienced EHD designer.

To change any of these variables, the mouse cursor must be positioned within the "Initial Guesses" menu command and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and they can be selected by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the desired variable is highlighted. When the variable has been chosen, a prompt indicating the chosen variable, the current value, and a box for entering the new value is displayed. A new value can be entered from the keyboard followed by a keyboard return which results in changing the value or the default value can be retained with just the keyboard return. After the keyboard return, the prompt disappears and the new value is stored for future use in the EHD analysis.

2.6. Grid Definition

The control volume finite element method requires the definition of a grid mesh within the lubricant for the EHD analysis and within the solid for the internal stress analysis. This is accomplished by setting the following variables in the menu command entitled "Grid Definition":

1) Number of nodes in the x-direction - Used to define the grid points along the rolling direction from the inlet zone to the exit zone. The maximum number of grid points is 201.
2) Number of nodes into the lubricant - Used to define the grid points within the lubricant from the lower solid to the upper solid. The maximum number of grid points is 13.
3) Number of nodes into the solid - Used to define the grid points within the solid from the surface into the solid. The maximum number of grid points is 101.

4) Grid sections - Used to define the number of sections in the rolling direction from the inlet zone to the exit zone. This command includes defining the number of sections, the number of grid points in each section, and the inlet and exit positions of each section. This command should only be used by the experienced EHD designer and care must be taken to ensure the following: 1) The sum of the number of grid points in each section must exactly equal one less than the number of grid points in the x-direction; and 2) the exit position of one section must be the same value as the inlet position of the adjacent section to ensure a consistent grid.

To change any of these variables, the mouse cursor must be positioned within the "Grid Definition" menu command and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and they can be selected by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the desired variable is highlighted. When the variable has been chosen, a prompt indicating the chosen variable, the current value, and a box for entering the new value is displayed. A new value can be entered from the keyboard followed by a keyboard return resulting in the changing of the value or the default value can be retained with just the keyboard return. After the keyboard return, the prompt disappears and the new value is stored for use in future EHD analyses.

3. EHD Analysis

The fourth menu command entitled "EHD Analysis" contains the six EHD analysis models available for execution as shown below:

1) Newtonian Isothermal - EHD Analysis based on the Newtonian fluid model assuming a constant temperature distribution within the lubricant.
2) Newtonian Thermal - EHD Analysis based on the Newtonian fluid model including the effects of temperature within the lubricant.
3) Non-Newtonian Hyperbolic Isothermal - EHD Analysis based on the non-Newtonian hyperbolic fluid model assuming constant temperature distribution within the lubricant.
4) Non-Newtonian Eyring Isothermal - EHD Analysis based on the non-Newtonian Re-Eyring fluid model assuming constant temperature distribution within the lubricant.
5) Non-Newtonian Eyring Thermal without the thermal expansion of the solid - EHD Analysis based on the non-Newtonian Re-Eyring fluid model including the effects of temperature within the lubricant.
6) Non-Newtonian Eyring Thermal with the thermal expansion of the solid - EHD Analysis based on the non-Newtonian Re-Eyring fluid model including the effects of temperature within the lubricant and the effects of thermal expansion of the solids.

This menu command is initially disabled until a lubricant is chosen specifying which EHD model is to be used. The following sections will describe the procedure for choosing a lubricant type and name.

3.1. Lubricant Type

The first step in selecting a lubricant is to move the mouse cursor into the lubricant area (blue area labeled "lubricant" between the cylinders) and press one of the mouse buttons. The lubricant area is then highlighted in red and the lubricant types are displayed in boxes along with an exit box. The two choices are "NEWTONIAN" and "NON-NEWTONIAN". To make a selection, the mouse cursor must be positioned within one of the boxes and one of the mouse buttons must be pressed which results in the chosen box being highlighted. If the "EXIT" box is selected, the display is erased and the lubricant area returns to its original color just as if the lubricant area had never been selected. If the "NEWTONIAN" box is chosen, a list of lubricant names appears. If the "NON-NEWTONIAN" box is chosen, the types of non-Newtonian lubricants are displayed. The two choices are "HYPERBOLIC" and "EYRING" and choosing one of these is handled exactly as choosing a lubricant type which results in the lubricant name display. However, if the "EXIT" box is now selected, the display returns to the initial lubricant types.

3.2. Lubricant Names

The final step in selecting a lubricant is to choose the lubricant name. As indicated in the previous section, when the lubricant type (Newtonian or non-Newtonian) has been chosen, a list of lubricant names is displayed. The choices are MINERALOIL, PARAFINIC, and OTHER along with an EXIT box. To select one of these choices, the mouse cursor must be positioned within the appropriate box and one of the mouse buttons must be pressed which results in the chosen box being highlighted. If the "EXIT" box is selected, the display returns to the previous display. If "MINERALOIL" or "PARAFINIC" is selected, the properties associated with the lubricant are read from a data file and displayed on the screen as described in Chapter AII - section 2.4. If "OTHER" is selected, the user is prompted to enter a new lubricant name and, if a data file exists, the values are read and displayed. However, if this is a new lubricant, the user is prompted with a statement indicating that the file does not exist (along with the name previously entered within quotes) and a question asking "[illegible] this what you typed (y/n)?" Entering n (for no) allows the user to reenter the lubricant name. Entering y (for yes) results in another question asking "Do you want to create a new file (y/n)?" Entering y (for yes) results in the creation of a new lubricant data file in the user's directory consisting of the values entered from the lubricant properties page. Entering n (for no) results in no data file created in the user's directory; however, the lubricant can still be used in the current session. This feature allows the user to build a data base of lubricant names.

3.3. Creating a Data Base

A special feature of this graphics package is the ability to create a lubricant file data base. This is accomplished in two ways. The first method results by choosing "OTHER" as a lubricant name (see previous section), entering the new lubricant to be defined, and answering y (for yes) to the question "Do you want to create a new file (y/n)?" The new properties can now be entered followed by selecting the "OK" box (see Chapter AII - section 2.4.). These new properties are now stored in a data file under the name of the lubricant in the user's current directory. It is very important to select the "OK" box instead of the "CANCEL" box. Choosing the "CANCEL" box overrides the creation of the new file and returns the display to the original set-up display as if no lubricant had been chosen.

The second method results from selecting the "OK" box on the lubricant properties page when working with a pre-defined lubricant (ie. mineraloil, parafinic, etc.). The user is prompted with a question asking "Do you want to store the new values (y/n)?" Entering n (for no) leaves the original values in the lubricant data file whereas entering y (for yes) results in another prompt for entering the file name to store the values. The purpose of this is twofold: 1) It keeps the user from accidently over writing the original values in the data file; and 2) It allows the user to create variations of a particular lubricant (ie. mineraloil1, mineraloil2, etc.).

3.4. EHD Execution

After a lubricant has been chosen, the EHD analysis can be performed. At the beginning of this chapter, a list of the possible EHD analyses was given and it was mentioned that the menu command containing them was disabled. With the lubricant chosen, the menu command entitled "EHD Execution" is enabled along with the analyses corresponding to the type of lubricant chosen (ie. Newtonian lubricant enables items one and two). To perform one of these analyses, the mouse cursor must be positioned in the menu command entitled "EHD Execution" and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and they can be selected by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the desired analysis is highlighted. A prompt is then displayed for entering the file name to store the generated data which allows each analysis to be stored in separate files. After entering the file name, the object file corresponding to the analysis chosen is compiled and the resulting executable is run using the predefined variables. While the analysis is being performed, no other action can take place unless the plot flag (see Chapter AII - section 2.5.)

has been set to 1 (plot each iteration). When each iteration is plotted, a new window is created containing a view of the current film thickness and pressure profile. This window appears for a set period of time and is then disposed of and execution continues.

At the conclusion of the analysis, the original variable declaration page is displayed and the menu item corresponding to the analysis performed is disabled until a lubricant with this same type is chosen again. Now, the menu item for viewing the film thickness and pressure is enabled and if a thermal analysis was chosen, the temperature distribution and velocity profile can also be viewed (see Chapter AII - section 5.). Other options include performing another EHD Analysis and computing the internal stresses (see Chapter AII - section 4.).

4. Stress Calculation Within the Solid

At the initial start up of setup*, the fifth menu item entitled "Stress Calculation" is disabled and it remains so until an EHD analysis is performed. The contents of this menu are shown below:

1) Mechanical Stresses - This item performs the calculation of the maximum internal shear stresses based on the pressure within the lubricant (thus titled mechanical stresses). These stresses can be calculated following any of the six EHD analyses.
2) Thermal Stresses - This item performs the calculation of the maximum internal shear stresses based on the temperature distribution within the lubricant (thus titled thermal stresses). These stresses can only be calculated following one of the three thermal EHD analyses. Calculation of the thermal stresses requires a significant amount of cpu computing time.

After an EHD analysis has been performed, the menu command entitled "Stress Calculation" is enabled which contains the "Mechanical Stress" item and "Thermal Stress" item (if a thermal analysis has been performed). To perform one of these analyses, the mouse cursor must be positioned within the menu command and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and they can be selected by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the desired analysis is highlighted. A prompt is then displayed for entering the EHD data file to be used in the calculation (with the default file name being the most recently created EHD data file) followed by a prompt for entering the file name to store the generated data which allows each analysis to be stored in separate files. When entering the EHD data file to be used, if there is no file with the given name in the user's directory, an error prompt is displayed indicating that the file does not exist and a new file name must be entered. After entering the EHD file name and the mechanical stress output file name, the object file corresponding to the analysis chosen is compiled and the resulting executable is run. While the analysis is being performed, no other action can take place.

At the conclusion of the analysis, the original variable declaration page is displayed and the menu item corresponding to the analysis just performed is disabled until another EHD analysis is performed. Now, the calculated stresses can be viewed (see Chapter AII - section 5.).

5. Viewing the Results

The sixth menu item entitled "View Results" is used for displaying the generated data from the EHD analyses and stress calculations and consists of the following items:

1) Film thickness, pressure, temperature - This item allows the user to view the film thickness, pressure, and temperature (if a thermal EHD analysis has been performed) profiles within the lubricant. The film thickness and pressure are displayed as line plots and the temperature is displayed as a two-dimensional color "contour" plot.
2) Velocity - This item allows the user to view the velocity profile within the lubricant.
3) Film thickness, pressure, temperature, velocity - This item allows the same view as in 1) along with the velocity profile within the lubricant.

4) Mechanical Stresses - This item allows the user to view the maximum mechanical shear stresses within the solid. The stress profile is displayed as a 2-dimensional color "contour" plot.

5) Thermal Stresses - This item allows the user to view the maximum thermal shear stresses within the solid. The stress profile is displayed as a 2-dimensional color "contour" plot.

6) Mechanical and Thermal Stresses - This item allows the user to view both the maximum mechanical and thermal shear stresses within the solid along with the combination of the two or the total maximum shear stress within the solid. The three stress profiles are displayed as 2-dimensional color "contour" plots.

7) Comprehensive View - This item allows the user to view all of the generated data as defined in items 1 and 4-6.

At the initial start up of setup*, the sixth menu item is disabled and it remains so until the respective analyses are performed. If the user has performed an EHD analysis or stress calculation in a previous session, he can enable the corresponding items in the "View Results" menu item to allow viewing these results. To accomplish this, the last menu command entitled "Previous Executions" must be used. This menu command contains items to enable the "View Results" items based on the analysis performed. For example, if a thermal Newtonian EHD analysis has been performed, the user must select the item "Thermal Newtonian analysis has been performed" and the first three menu items will be enabled in the "View Results" menu command.

Otherwise, after an EHD analysis has been performed, the menu command entitled "View Results" is enabled along with item one (items two and three are also enabled if a thermal EHD analysis was performed). The remaining items become enabled as the respective analyses are performed (ie, mechanical stresses, etc.). To view any of the results, the mouse cursor must be positioned within the menu command and one of the moues buttons must be pressed and held down. The contents of the menu are now displayed and they can be selected by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the desired item is highlighted. A prompt for entering the type of units for viewing the results is displayed. The results can be viewed in any of the three units even though the analysis was performed with a specific set of units. Entering m (for metric) shows the results with metric units; entering e (for English) allows the results to be viewed in English units; and entering n (for non-dimensional) shows the results in non-dimensional form. After entering the viewing units, prompts for entering the necessary data files are displayed. When entering these data files, if there is no file with the given name in the user's directory, an error prompt is displayed indicating that the file does not exist and a new file name must be entered. After entering all of the necessary information, the object file corresponding to the selection is compiled and the resulting executable is run resulting in a new window being created with the chosen view displayed. This display consists of a view of the data and a color grid indicating the values corresponding to the colors in the profiles. A special feature of this display allows the user to examine the value at any location within a particular profile. This is accomplished by moving the mouse cursor to any position within a profile and pressing one of the mouse buttons. The location is then displayed along with the corresponding value at that location. Another special feature allows the user to view multiple files at the same time. This option can only be used when viewing a single "item" (ie. items 1, 4, and 5). To perform a multiple view, the menu command entitled "Multiple Views" in the display window is used. To perform a second (or more) view, the mouse cursor must be positioned within the menu command entitled "Multiple Views" and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and the new view can be performed by dragging the mouse cursor (with the mouse button still held down) down the list and releasing the mouse button when the item "Another View" is highlighted. A prompt is then displayed for entering the new file name to be used in the view. This option can be used a maximum of four times which allows the user to compare four different situations at the same time to analyze the effects of varying a certain operating parameter (ie. applied load) or using different lubricants or materials.

To terminate the display, the menu command (in the display window) entitled "Quit" with only a single menu item is chosen and the window is disposed of returning the user to the original variable declaration page. At this point, a "complete" EHD analysis has been performed and the user can start over or terminate execution of the graphics package.

6. Terminating Execution

When the user finishes using setup*, execution can be terminated by using the first menu command entitled "QUIT." To do this, the mouse cursor must be positioned within the menu command and one of the mouse buttons must be pressed and held down. The contents of the menu are now displayed and the single item can be selected by dragging the mouse cursor (with the mouse button still held down) to the item and releasing the mouse button. The main setup* window is disposed of and the unix prompt appears on the screen.

INDEPENDENT ANALYSIS

As mentioned in the description of the object files in Chapter AI - section 1.2., the EHD analyses, stress calculations, and viewing results can be performed independently of the main executable setup*. However, before this can be done, a few initial steps must be taken. The first step is to compile the appropriate object file as discussed in Chapter AI - section 2. and the remaining steps are discussed in the following sections.

1. EHD Analysis

The only other step needed in performing an independent EHD analysis is to create an input file under the name "ehdin." The easiest way to accomplish this is to run the main executable setup* and perform at least one of the EHD analyses. Upon termination of setup*, there will be a file named "ehdin" in the user's directory with the values used in the most recent EHD analysis. The values in this file can be changed by editing the file. A second way is to create "ehdin" separately from setup*. In order to get the correct variables defined on the correct line (in ehdin), a copy of the subroutine "EhdFile" from the main source code "setup.F" should be obtained as this shows the order of the variables. This method requires an understanding of what each variable name used in the EHD analysis corresponds to. Once the appropriate object file has been compiled and "ehdin" has been created, the analysis can be performed by typing "a.out" at the unix prompt. The contents of ehdin are shown below:

ehdin
Applied load (dimensionless)
Equivalent Modulus of Elasticity
Slip
Average speed
Modulus of Elasticity for upper solid
Modulus of Elasticity for lower solid
Poisson's ratio for upper solid
Poisson's ratio for lower solid
Radius of upper solid
Radius of lower solid
Initial guess for exit film thickness
Dimensionless film thickness constant
Number of nodes in the rolling direction
Number of nodes into the lubricant
Initial guess for exit nodal point
Temperature convergence criteria
Maximum number of iterations for Newton-Raphson technique
Maximum number of iterations for Control Volume method
Plot flag
EHD output data file name
Inlet lubricant temperature
Ambient viscosity of lubricant
Ambient density of lubricant
Roeland's viscosity model exponent
Thermal conductivity of lubricant
Specific heat of lubricant
Thermal conductivity of solid
Specific heat of solid
Density of solid
Temperature-viscosity constant
Coefficient of thermal expansivity
Dowson-Higginson density model constant 1
Dowson-Higginson density model constant 2

Pressure viscosity exponent
Lubricant name
velocity output data file name
Flag (1=isothermal, 2=thermal
Limiting shear stress*
Limiting shear stress**
Shear stress constant**

Number of grid sections
Number of nodes in section, inlet position, exit position

2. Stress Calculation

Before an independent stress calculation can be performed, an EHD analysis has to have been performed and the generated data must be stored in a file. Having an EHD data file, the only other step needed is to create an input file under the name "mstressin" for calculating the maximum mechanical shear stresses or "tstressin" for calculating the maximum thermal shear stresses. The contents of these files are shown below:

mstressin	**tstressin**
EHD data file name	EHD data file name
Output stress data file name	Output stress data file name
Number of nodes into the solid	Number of nodes into the solid
	Which solid (1=upper, 2=lower)

Once an EHD analysis has been performed, the appropriate object file has been compiled, and the input file has been created, the stress calculations can be performed by typing "a.out" at the unix prompt.

3. Viewing the Results

Because there are seven possible views that can be created, each one will be handled separately.

* This value is only needed when the Eyring fluid model is chosen
** These values are only needed when the Hyperbolic fluid model is chosen

1) Film thickness, pressure, and temperature within the lubricant - Before this view can be displayed, an EHD analysis must be performed and the generated data must be stored in a file. Having an EHD data file, the only other step is to create an input file under the name "plotin" with the following items:
    1 (for menu item number from setup*)
    EHD data file name
    viewing units (1=metric, 2=English, 3=non-dimensional)
2) Velocity within the lubricant - Before this view can be displayed, a thermal EHD analysis must be performed and the generated velocity data and the EHD data must be stored in separate files. Having the velocity data file and the EHD data file, the only other step is to create an input file under the name "plotin" with the following items:
    2 (for menu item number from setup*)
    EHD data file name
    Velocity data file name
    viewing units (1=metric, 2=English, 3=non-dimensional)

3) Film thickness, pressure, temperature, and velocity within the lubricant - Before this view can be displayed, a thermal EHD analysis must be performed and the generated data must be stored in a file. Having an EHD data file and a velocity data file, the only other step is to create an input file under the name "plotin" with the following items:

   3 (for menu item number from setup*)
   EHD data file name
   Velocity data file name
   viewing units (1=metric, 2=English, 3=non-dimensional)

4) Mechanical Stresses within the solid - Before this view can be displayed, an EHD analysis must be performed with the generated data stored in a file and the mechanical stress calculation program must be performed with the generated data stored in a file. With these files, the only other step needed is to create an input file under the name "plotin" with the following items:

   4 (for menu item number from setup*)
   EHD data file name
   Mechanical stress data file name
   viewing units (1=metric, 2=English, 3=non-dimensional)

5) Thermal stresses within the solid - Before this view can be displayed, a thermal EHD analysis must be performed with the generated data stored in a file and the thermal stress calculation program must be performed with the generated data stored in a file. With these files, the only other step needed is to create an input file under the name "plotin" with the following items:

   5 (for menu item number from setup*)
   EHD data file name
   Thermal stress data file name
   viewing units (1=metric, 2=English, 3=non-dimensional)

6) Mechanical and Thermal stresses within the solid - Before this view can be displayed, a thermal EHD analysis must be performed with the generated data stored in a file, the mechanical stress calculation program must be performed with the generated data stored in a file, and the thermal stress calculation program must be performed with the generated data stored in a file. With these files, the only other step needed is to create an input file under the name "plotin" with the following items:

   6 (for menu item number from setup*)
   EHD data file name
   Mechanical stress data file name
   Thermal stress data file name
   viewing units (1=metric, 2=English, 3=non-dimensional)

7) Comprehensive view - Before this view can be displayed, a thermal EHD analysis must be performed with the generated data stored in a file, the mechanical stress calculation program must be performed with the generated data stored in a file, and the thermal stress calculation program must be performed with the generated data stored in a file. With these files, the only other step needed is to create an input file under the name "plotin" with the following items:

   7 (for menu item number from setup*)
   EHD data file name
   Mechanical stress data file name
   Thermal stress data file name
   viewing units (1=metric, 2=English, 3=non-dimensional)

Once the appropriate analyses have been performed, the generated data has been stored in separated files, the object file (plot.o) has been compiled, and the input file "plotin" has been created, the appropriate view can be displayed by typing "a.out" at the unix prompt.

SUMMARY OF A COMPLETE EXECUTION

This user's guide has attempted to provide a complete description of all facets of the Graphics package. With this information, the user can refer to this section for a basic overview of one complete execution of setup*.

To begin execution of setup*, type "setup" at the unix prompt. Use the mouse to "CONTINUE" through the first two "pages" of introduction and to select the type of units desired. Set up the loading conditions, material properties, and initial guesses (if necessary) for performing the analyses. Position the mouse cursor within the lubricant area and press a mouse button to obtain the lubricant types page. Choose a lubricant type, lubricant name, define the lubricant property values, and choose the "OK" box.

With all of the variables defined and the lubricant chosen, select one of the enabled items within the fourth menu command entitled "EHD Analysis" and enter an EHD output file name and a velocity data file name. Upon completion of the EHD analysis, select the "mechanical stress" item within the fifth menu command entitled "Stress Calculation," enter the EHD data file name defined previously, and enter a mechanical stress output data file name. Upon completion of this analysis, select the "thermal stress" item within the fifth menu command entitled "Stress Calculation" (only enabled if a thermal EHD analysis was performed), enter the EHD data file name defined previously, and enter a thermal stress data file name. Upon completion of this analysis, any and all of the results can be viewed by selecting one of the items in the sixth menu command entitled "View Results." When selecting any of these items, the units to view the results must be entered (note that the viewing units do not necessarily have to be the same as those chosen at the beginning of setup*) along with the appropriate data file names defined previously. With the view displayed, exact values anywhere within the profiles can be displayed by moving the cursor to the desired location and pressing one of the mouse buttons. Also. another view can be shown simultaneously (if viewing items 1, 4, or 5) by selecting the item "Another View" from the menu command entitled "Multiple Views." When the user is finished viewing the results, select the "QUIT" menu command in the view window to return to the variable declaration page. After all the analyses have been performed and all the generated data have been viewed, the user can start over with a new EHD analysis or terminate execution of setup* completely by selecting the "Quit this Execution" item in the first menu item entitled "QUIT."

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